Sweet potato yields and nutrient dynamics after short-term fallows in the humid lowlands of Papua New Guinea

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Abstract

Shifting cultivation is common in the humid lowlands of Papua New Guinea but little is known about the effect of different fallows on sweet potato (*Ipomoea batatas*) yield and nutrient flows and pools in these systems. An experiment was conducted in which two woody fallow species (*Piper aduncum* and *Gliricidia sepium*) and a non-woody fallow species (*Imperata cylindrica*) were planted and slashed after one year. Sweet potato was grown for two consecutive seasons (1 year) after which the fallows and yields were compared with yields from continuously cropped plots. The experiment was conducted on a high base status soil (Typic Eutropepts). In the first season, marketable sweet potato yield after piper and imperata was about 11 t ha^{-1} but yields after gliricidia and under continuous cropping were significantly lower. Vine yield was similar for the continuously cropped plots and for the sweet potato after piper and gliricidia, but significantly lower than after imperata. The effects of the fallows on sweet potato yield lasted only one season. In the second season after the fallow, sweet potato yields were higher, which was contributed to lower rainfall. Nutrient budgets showed that the three fallow species (piper, gliricidia and imperata) added insufficient amounts of nitrogen, phosphorus and potassium for the removal of these nutrients by two consecutive seasons of sweet potato. From a yield point of view there seems no benefit in having a nitrogen-fixing fallow species like *Gliricidia sepium* in sweet potato based systems on high base status soils.

Additional keywords: improved fallow, natural fallow, *Piper aduncum*, *Gliricidia sepium*, *Imperata cylindrica*, crop yield, nutrient budgets

Introduction

Shifting cultivation is an important land use system in many parts of the humid tropics. If the fallow period is shortened there is a need to introduce fallow species (hereafter referred to as fallows) that improve soil fertility more rapidly than would occur under natural fallow because shorter fallow periods often result in subsequent lower crop yields (Buresh & Cooper, 1999). Such improved fallows are rapidly spreading in several regions of the tropics and some of the comparative advantages of woody over herbaceous fallows include firewood production, weed suppression and improved soil physical properties (Sanchez, 1999). Many of the beneficial effects of fallows as well as the underlying mechanisms remain to be quantified (Sanchez *et al.*, 1997).

Shifting cultivation is common in the humid lowlands of Papua New Guinea. About 75% of the country is still under forest and only 13% is used for agriculture at relatively high levels of land use intensity; the remaining 12% is used at low intensity (Bellamy & McAlpine, 1995). The doubling of the human population in Papua New Guinea between the mid-1960s and mid-1990s has not led to a significant increase in land under cultivation. Instead, the increased food and cash crop production has shortened the length of the fallow period (Allen *et al.*, 1995; Hartemink & Bourke, 2000).

The secondary fallow vegetation in parts of the humid lowlands of Papua New Guinea is dominated by *Piper aduncum*, a shrub indigenous to tropical America. *Piper aduncum* (hereafter referred to as piper) was first observed in Papua New Guinea in the 1930s and was not widespread in the 1970s. However, by the mid-1990s it is very common in the humid lowlands but can also be found in the highlands (Hartemink, 2001). Short-term (< 2 years) piper fallows are followed by food crops including sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), sugarcane (*Saccharum* sp.) and bananas (*Musa* sp.). Sweet potato is the main staple crop; the larger tubers are used for human consumption whereas the smallest ones are used as pig feed. Vines and leaves are occasionally eaten as green vegetable but their main use is also pig feed. Sweet potato production is increasing in the lowlands below 600 m altitude where it has replaced traditional taro to a large degree (Bourke, 1985b).

Although the aggressive invasion of piper has been described, including its possible effect on Papua New Guinea's rich biodiversity (Rogers & Hartemink, 2000; Saulei & Swaine, 1988), there is no information available on the effect of piper fallows on soil and crop productivity. It is not known whether piper fallows are more productive than other natural fallows like *Imperata cylindrica* grasslands (hereafter referred to as imperata). Imperata fallows are also common in the lowlands of Papua New Guinea and – like in other parts of the world – imperata in Papua New Guinea is not confined to the poorest soils (Santoso *et al.*, 1997).

In Papua New Guinea some alley-cropping (hedgerow-intercropping) experiments have been conducted but like elsewhere in the humid tropics mixed results were obtained (Brook, 1999; Louman & Hartemink, 1998; Sayok & Hartemink, 1998). Improved fallows may be more efficient than alley-cropping or traditional fallows in restoring soil fertility (Buresh & Cooper, 1999). In some parts of the world, *Gliricidia sepium* (hereafter referred to as gliricidia) is planted as improved fallow and gliricidia is one of the most widely cultivated leguminous multipurpose trees (Simons & Stewart, 1994). Gliricidia is common in Papua New Guinea where it is used as shade tree in cocoa plantations. From a soil nitrogen (N) point of view it is a suitable species as it grows fast and thus takes up and recycles N within the soil-plant system and gliricidia also fixes atmospheric N (Young, 1997).

To investigate the effects of piper, imperata and gliricidia fallows on sweet potato yields a field experiment was conducted in a farming area where piper dominates the secondary fallow vegetation, but where imperata grasslands are also common. One-year old fallows were slashed after which two crops of sweet potato were grown. The overall aim of the experiment was to quantify nutrient dynamics and productivity of short-term fallows and to study their effects on soil chemical and physical properties and nutrient budgets.

Materials and methods

Site

The experiment was conducted near Hobu village (6°34′S, 147°02′E), which is located about 25 km north of the city of Lae in the Morobe Province of Papua New Guinea. Rainfall records for the site were only available since November 1996 when the experiment was started. In 1997, total rainfall was 1,897 mm, which is well below the long-term average at the University of Technology, 15 km south of the experimental site. The low rainfall was due to the El Niño/Southern Oscillation climatic event, which hit the Pacific severely in 1997–'98. In the first six months of 1998 more rain fell than in the whole of 1997. March 1998 was a particularly wet month with 725 mm of rain. At the University of Technology total rainfall in 1997 was only 2,594 mm, against the long-term (20 years) annual mean of 3,789 mm. Daily rainfall during the experimental period is presented in Figure 1, and shows the relatively dry period in the second half of 1997 due to El Niño. Temperature data are not available for the site but average daily temperatures at the University of Technology are 26.3 °C. Since the University is at a lower altitude (65 m a.s.l.) temperatures at Hobu are probably on average slightly lower.

Soils

The experimental site is at the footslopes of the Saruwaged mountain range, the major landmass of the Huon peninsula, and is located on an uplifted alluvial terrace at an altitude of 405 m a.s.l. with slopes 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 are layered with water-worn gravelly and stony layers below 0.2 m depth. Much of the gravel and many stones are rotten and effective rooting depth is over 0.7 m. Air-dried and sieved (< 2 mm) soil had the following properties in the top 0.12 m: pH H_2O (1:5 w/v) = 6.2, organic C (dry combustion) = 55 g kg^{-1}, available P (Olsen) = 9 mg kg^{-1}, CEC (NH_4Oac, pH7) = 400 $mmol_c kg^{-1}$, exchangeable Ca = 248 $mmol_c kg^{-1}$, exchangeable Mg = 78 $mmol_c kg^{-1}$, exchangeable K

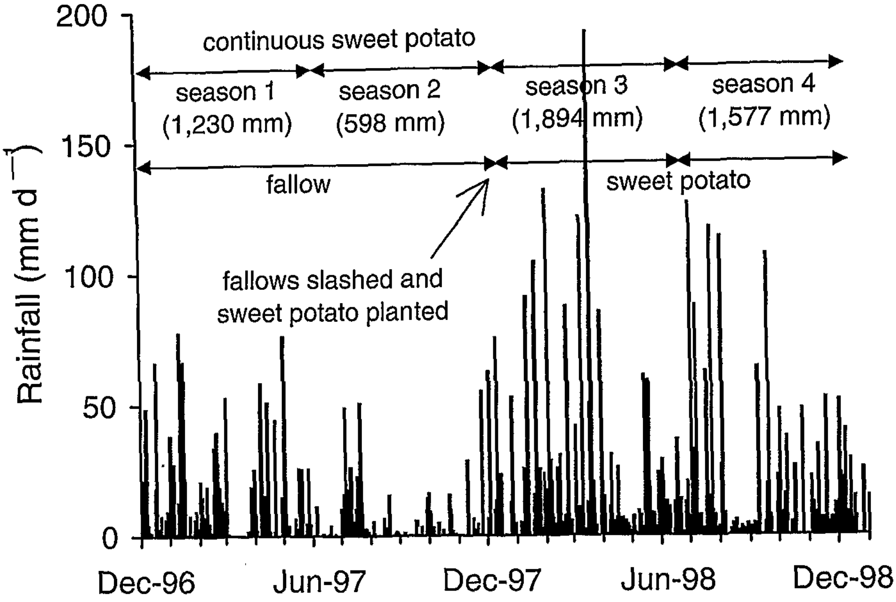

Figure 1. Daily rainfall (mm) during the four seasons (December 1996 – November 1998) at the experimental site (Hobu village) in the humid lowlands of Papua New Guinea.

= 16.9 $\text{mmol}_c\,\text{kg}^{-1}$, clay = 480 g kg^{-1}, sand = 360 g kg^{-1} and bulk density = 0.82 t m^{-3}. Soils in the area are not enriched by volcanic ashes, which has occurred in many parts of Papua New Guinea (Bleeker, 1983). So the low bulk density is probably related to the high soil organic C contents, which are often negatively correlated with bulk density. The soils are classified as mixed, isohyperthermic, Typic Eutropepts (USDA Soil Taxonomy) or Eutric Cambisols (World Reference Base). Inceptisols are the commonest soils in Papua New Guinea and are estimated to cover approximately 40% of the country (Bleeker, 1983). Inceptisols are widely used for agriculture (Freyne & McAlpine, 1987).

The experiment

An area of about 0.5 ha secondary vegetation was slashed manually at the beginning of November 1996. The site had been intensively used for growing food crops but lay fallow since 1992. The vegetation consisted mainly of *Piper aduncum* and to a lesser extent of *Homolanthus* sp., *Macaranga* sp., *Trichospermum* sp. and *Trema orientalis* (Hartemink & O'Sullivan, 2001). All vegetation debris was removed and no burning was practised, which follows the land-clearing practices of local farmers.

Sixteen 6.0 m × 6.0 m plots were laid out and four treatments were assigned to the plots in a randomized complete block design with four replications. Blocks were separated by 2–3 m wide paths. At the end of November 1996 the fallow plots were planted. Four plots were planted with seedlings (0.4 m) of *Piper aduncum* and four plots with *Gliricidia sepium* cuttings (0.4 m). Both species were planted at 0.75 m × 0.75 m (17,778 plants ha^{-1}). In four plots the vegetation consisted of natural regrowth that was immediately dominated by *Imperata cylindrica*.

In the remaining four plots sweet potato cv. Hobu 1 was planted. Hobu 1 is a widely grown local cultivar with red skin tubers and white flesh. The cultivar appears not to be very susceptible to sweet potato weevils, which is an important pest of sweet potato in Papua New Guinea (Powell *et al.*, 2001). These sweet potato plots were continuously cropped for four seasons (see Figure 1). Planting material was obtained from local gardens and consisted of vine cuttings that were planted almost vertically using a stick. One cutting of about 0.4 m length with 4 to 6 nodes was planted per hill, which generally gives the highest tuber yield per ha (Levett, 1993). Cuttings were planted at 0.75 m × 0.75 m (17,778 plants ha^{-1}).

After one year (20–24 November 1997), the fallow vegetation was cut at ground level. From the piper and gliricidia plots the inner 36 (of the 64) plants of a plot were harvested to avoid possible edge effects. Stems were removed from the plots; all other plant parts were left behind as surface mulch. On 26 November 1997, the cleared plots were planted with sweet potato similar to the continuously cropped plots. No tillage was done and the plots were cropped with sweet potato for two seasons. The sweet potato growing periods lasted for about 170 days after which the plots were harvested. Vines were cut at ground level, weighed, and removed from the plot. Vine removal is also practised by the local farmers, which may be related to the vines' allelopathic effects that alter nutrient uptake (Walker *et al.*, 1989). To avoid possible edge effects, in each plot the inner 36 (of the 64) sweet potato plants were harvested. Tubers were manually dug, counted and separated into marketable tubers (> 100 g) and non-marketable tubers (< 100 g), after which they were removed from the plot. All plots were replanted immediately after the harvest. Weeds were pulled up manually and left behind on the surface to avoid nutrient removal. No mounds or ridges were constructed for the sweet potato, which is in accordance with farmers' practices. No biocides or other inputs were used in the experiment.

Rainfall in the first cropping season of the continuously cropped plots was 1,230 mm and 598 mm rain fell in the second season. So rainfall during the fallow period was 1,828 mm. In the first and second season after the fallow, rainfall was 1,894 mm and 1,577 mm, respectively (Figure 1).

Plant sampling and analysis

The sweet potato marketable tubers, non-marketable tubers and vines were weighed at harvest, and about one kg of vines per plot and three to five tubers were taken for dry matter determination and nutrient analysis. The plant samples from the fallow and sweet potato harvests were taken to the laboratory where they were rinsed with distilled water and oven-dried at 70 °C for 72 hours. Samples were ground (mesh 0.2 mm) before being sent for nutrient analysis. Nutrient analysis of the plant samples was conducted at the laboratories of the School of Land and Food of the University of Queensland, Australia. One subsample was digested in 5:1 nitric:perchloric acids and analysed for P, K, Ca and Mg using Inductively Coupled Plasma Mass Spectrometry

(ICP; Spectro Model P). A second subsample was analysed for C and N using a Leco combustion analyser. The analytical data were multiplied with the dry matter yield to obtain nutrient uptake in kg ha^{-1}.

Soil sampling and analysis

Soil samples for chemical analysis were taken (1) prior to planting the fallows, (2) after the fallows were slashed, and (3) after two seasons of sweet potato. In the continuously cropped plots, soil samples were taken prior to the first planting, after two seasons, and after four seasons. Soil samples were collected with an Edelman auger (diameter 0.05 m) at 12 random locations in a plot, mixed in a 20-litre bucket, after which a subsample of about 1 kg was taken. Air-dried samples were ground and sieved (2 mm) before being 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 carbon (C) and total N by Leco dry combustion; available P by Olsen; exchangeable cations and CEC by 1*M* NH_4OAc percolation (pH 7.0); particle size analysis by hydrometer.

Bulk density was measured when the soil samples for chemical analysis were taken. In each plot the 0–0.05 and 0.10–0.15 m soil horizons were sampled using two 100-ml cores per horizon. Cores were oven-dried at 105 °C for 72 hours. Soil moisture measurements using 150-ml tins were taken one week before the fallows were slashed and 12 and 24 weeks after sweet potato was planted. Measurements were duplicated in each plot. The soil samples were oven-dried at 105 °C for 72 hours, and gravimetric soil moisture contents were calculated. Gravimetric values were multiplied with the bulk density to obtain volumetric water contents (m^3 m^{-3}).

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}.

Statistical analysis

Standard deviations were calculated for aboveground biomass, nutrient content and nutrient removal. Analysis of variance was used to determine statistical differences in sweet potato yields, changes in soil chemical properties, and soil bulk density. Standard errors of the difference between means were calculated and in the discussion of the results the statistically significant difference was set at 5% ($P < 0.05$). All statistical analyses have been conducted with Statistix 8 for Windows.

Results

Nutrient input by the fallows

There were significant differences in aboveground biomass production and nutrient accumulation of the three fallows. One-year old piper had produced 13.7 t dry matter

(DM) ha^{-1}, against 23.3 t DM ha^{-1} produced by gliricidia and 14.9 t DM ha^{-1} by imperata (Table 1). The stems of piper and gliricidia were removed from the plots and total biomass returned was about 8 t DM ha^{-1} for piper and gliricidia and 14.9 t DM ha^{-1} for imperata. The gliricidia fallow returned the largest amounts of nutrients and 192 kg N ha^{-1} was present in the leaf mulch. Piper fallows returned the largest amounts of K (206 kg ha^{-1}). Imperata had accumulated the least nutrients of the three fallows. The P input by the aboveground biomass was similar for the three fallows (about 13 kg ha^{-1}).

Table 1. Above-ground biomass (t dry matter ha^{-1} ± 1 SD[1]), carbon (t ha^{-1} ± 1 SD) and nutrient (kg ha^{-1} ± 1 SD) content, of one-year old *Piper aduncum*, *Gliricidia sepium* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea.

		Fallow species		
		P. aduncum	*G. sepium*	*I. cylindrica*
Biomass	Total produced	13.7 ± 1.3	23.3 ± 1.6	14.9 ± 2
	Returned to the soil[2]	7.8 ± 0.3	8.1 ± 0.6	all
C	Total produced	5.8 ± 0.6	10.4 ± 0.7	6.7 ± 0.9
	Returned to the soil	3.1 ± 0.2	3.5 ± 0.4	all
N	Total produced	120 ± 12	356 ± 11	76 ± 24
	Returned to the soil	97 ± 9	192 ± 21	all
P	Total produced	22 ± 2	36 ± 4	12 ± 4
	Returned to the soil	14 ± 2	12 ± 2	all
K	Total produced	299 ± 25	248 ± 15	89 ± 16
	Returned to the soil	206 ± 18	89 ± 12	all
Ca	Total produced	157 ± 20	312 ± 38	56 ± 18
	Returned to the soil	147 ± 19	222 ± 30	all
Mg	Total produced	45 ± 8	64 ± 12	29 ± 9
	Returned to the soil	40 ± 7	41 ± 13	all
S	Total produced	11 ± 1	25 ± 2	4 ± 2
	Returned to the soil	10 ± 1	12 ± 2	all

[1] SD = standard deviation.

[2] Returned to the soil when the fallows were slashed. *P. aduncum* and *G. sepium* stems were removed from the field; leaves, small branches and litter were returned to the soil.

Sweet potato yields after the fallows

In the first cropping season after the fallow, marketable sweet potato yield after piper and imperata was about 11 t ha^{-1}, which was significantly higher than the yield under continuous sweet potato or after gliricidia (Table 2). Marketable yield under continuous sweet potato cropping was only 7.8 t ha^{-1}. Variation in non-marketable tuber yield was large but differences were not statistically significant. Total tuber yield (marketable plus non-marketable tubers) was highest after piper (14.4 t ha^{-1}) and significantly lower after gliricidia (9.9 t ha^{-1}). Vine yield was similar under continuous sweet potato cropping and after piper and gliricidia. Vine yield was about 10 t ha^{-1} less after the imperata fallow and the difference with the other fallows was highly significant.

In the second season after the fallow, tuber yield was on average higher and fallow effects on marketable sweet potato yield were no longer present. Non-marketable tuber yield, however, was significantly lower after imperata but no differences were found after the other fallow crops. Vine yield after imperata was lower but not statistically different from the other fallow treatments. Total tuber yield in the second season was similar for all treatments and no difference in yield was found between previously fallowed plots and continuous sweet potato plots.

Cumulative total tuber yield over the two cropping seasons was about 29 t ha^{-1} for piper and imperata, 26 t ha^{-1} for gliricidia and less than 25 t ha^{-1} for the continuous sweet potato plots. The cumulative vine yield over the two seasons was between 53 and 60 t ha^{-1} for continuous sweet potato and sweet potato after gliricidia and piper fallow, but total vine yield was less than 40 t ha^{-1} after imperata fallow.

Biomass production of fallow and sweet potato

Total productivity of the fallow and continuous sweet potato systems can be assessed by the total dry matter that is removed from the field (i.e., tubers and vines from the sweet potato, and wood from the piper and gliricidia fallows). Table 3 presents the dry matter production of the four treatments. Continuous sweet potato had the highest dry matter production but more than 40% consisted of vines. Although the gliricidia fallow was followed by a lower tuber production, it yielded almost three times more wood. Gliricidia and imperata systems yielded comparable amounts of tuber dry matter but imperata had no additional useful products like wood.

Changes in soil chemical properties

Under continuous sweet potato cropping, the topsoil pH significantly declined with about 0.4 units and the change occurred in the first two seasons (Table 4). The soil acidification trend was accompanied by a significant decrease in exchangeable Ca, K and base saturation. Soil organic C and total N slightly increased during the first two cropping seasons but both significantly decreased during the subsequent two seasons of sweet potato cropping. After two years of sweet potato cropping available P had decreased by 4 mg kg^{-1}.

Table 2. Sweet potato yields (t fresh weight ha^{-1}) for two seasons after one-year fallow of *Piper aduncum, Gliricidia sepium* or *Imperata cylindrica*, and under continuous sweet potato cropping.

	Sweet potato yield					
	Marketable tubers (> 100 g)		Non-marketable tubers (< 100 g)		Vines	
	First season	Second season	First season	Second season	First season	Second season
Fallow species						
P. aduncum	11.2	13.4	3.1	2.1	30.4	22.9
G. sepium	8.4	14.3	1.6	1.8	31.6	26.1
I. cylindrica	11.3	15.2	1.5	1.1	20.7	18.9
Continuous sweet potato[1]	7.8	12.8	2.4	2.0	32.3	27.4
SED[2]	1.3	ns	ns	0.3	3.9	4.1

[1] Yields from the third and fourth season under continuous cropping.

[2] SED = standard error of the difference between means (9 df); ns = no statistical difference ($P > 0.05$).

Changes in soil chemical properties under the three different fallows followed by two seasons of sweet potato showed a similar pattern. The soils acidified significantly during the fallow period and the decrease in soil reaction was highest during the imperata fallow (–0.6 pH units). The pH change during the one-year piper and gliricidia fallows was about –0.4 units and the pH further decreased after two seasons of sweet potato. Fallow followed by two seasons of sweet potato decreased pH by 0.5 to 0.6 units.

Table 3. Sweet potato yield (dry matter; t ha^{-1}) under continuous cropping (four seasons), and after a one-year fallow of *Piper aduncum, Gliricidia sepium* or *Imperata cylindrica* followed by two seasons of sweet potato. Amounts removed from the plots (wood; tubers and vines) during the two years of the experiment.

	Continuous sweet potato	Sweet potato preceded by:		
		P. aduncum	*G. sepium*	*I. cylindrica*
Marketable tubers	16.2	7.9	7.1	8.0
Non-marketable tubers	4.9	1.6	1.2	0.8
Vines	15.5	7.6	8.3	5.9
Wood (stems)	0	5.9	15.2	0

Organic C increased during the fallow period, which was accompanied by an increase in total N. The increase was largest under gliricidia. During the subsequent sweet potato seasons, organic C contents decreased. Available P decreased under all fallows although the decrease was only statistically significant under the imperata fallow. Levels of exchangeable Ca decreased significantly during the imperata fallow but changes under the other fallows were not statistically significant. No changes were found in the exchangeable Mg of the soils under fallow followed by sweet potato. Exchangeable K decreased significantly during the piper fallow (–4.1 $\text{mmol}_c\ \text{kg}^{-1}$) and slightly increased after the piper fallow was slashed. Base saturation decreased significantly under gliricidia and imperata fallows (Table 4).

Changes in soil physical properties

Soil bulk density was measured at the start of the experiment, after one year when the fallows were slashed and after two seasons with sweet potato (Table 5). There were slight changes in soil bulk density and the pattern was the same under the three fallows. Bulk density in the 0–0.05 m soil horizon was about 0.60 t m^{-3} at the start and had increased by about 0.08 t m^{-3} after the fallows. After two crops of sweet potato, bulk density decreased in the 0–0.05 m soil horizons of the previously fallowed plots. In the 0.10–0.15 m soil horizon the same pattern was depicted although bulk density values were slightly higher. Under continuous sweet potato cropping, a slight decrease in bulk density was found in the 0–0.05 m soil horizon but an increase in the 0.10–0.15 m soil horizon.

After one year of fallow, moisture contents in the 0–0.05 m soil horizon were significantly lower under piper than under gliricidia and imperata. (Table 6). The difference with the moisture content of the soils under gliricidia was 0.06 $\text{m}^3\ \text{m}^{-3}$. This is remarkable as gliricidia had produced nearly 10 t DM ha^{-1} more biomass than piper (Table 2). Moisture contents in the 0.10–0.15 m soil horizon were also significantly lower under one-year old piper than under gliricidia. Soil moisture contents under imperata were closest to those under piper. Twelve weeks after the fallows were slashed moisture contents in the 0–0.05 m soil horizon were highest in the plots previously fallowed with imperata. Twenty-four weeks after the fallows had been slashed no significant differences in soil moisture content were found between plots.

Nutrient removal

Nutrient removal was calculated for each of the fallow and sweet potato seasons (Table 7). The removal was particularly high for the first season in the continuous sweet potato plots and for the gliricidia. Nutrient removal of sweet potato after the different fallows matches the tuber yield levels, i.e., more yield more removal. From the imperata fallow the least nutrients were removed because no nutrients were removed when the fallows were slashed and the subsequent sweet potato crop produced significantly less vines (Table 2). Figure 2 shows that total nutrient removal was very high for continuous sweet potato, but that also the gliricidia fallow followed by two sweet potato crops removed large amount of nutrients, particularly Ca and Mg.

Table 4. Soil chemical properties under continuous sweet potato cropping, and before and after a one-year fallow with *Piper aduncum*, *Gliricidia sepium* or *Imperata cylindrica* followed by two seasons of sweet potato. Sampling depth 0–0.15 m.

	Sampling time	pH H_2O 1:5 w/v	Org. C	Total N	P-Olsen	CEC pH 7	Exch. cations			Base saturation
							Ca	Mg	K	
			---- ($g\ kg^{-1}$) ---		($mg\ kg^{-1}$)	--------- ($mmol_c\ kg^{-1}$) ---------				(%)
Continuous sweet potato	Before 1st planting	6.2	69.9	6.0	10	405	268	61	12.2	84
	After two seasons	5.8	76.8	7.3	8	433	238	69	10.2	74
	After four seasons	5.8	71.3	5.9	6	466	227	59	8.4	63
	SED[1]	0.12	1.55	0.37	1.1	11.8	15.4	1.8	1.5	3.3
P. aduncum fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.2	68.4	6.2	8	407	242	60	12.5	77
	After the fallow	5.8	71.0	7.2	6	440	219	63	8.4	67
	After sweet potato	5.6	72.3	5.6	5	421	209	62	10.2	67
	SED	0.07	ns	0.59	ns	ns	ns	ns	0.51	ns
G. sepium fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.2	67.8	6.2	6	393	252	63	9.5	83
	After the fallow	5.9	82.2	7.7	5	416	220	68	7.9	71
	After sweet potato	5.7	77.6	6.1	4	488	233	62	7.2	63
	SED	0.13	3.42	0.35	ns	35.5	ns	ns	ns	6.4
I. cylindrica fallow followed by two seasons sweet potato (1 year)	Before the fallow	6.3	70.1	6.7	7	409	279	60	11.6	86
	After the fallow	5.7	76.9	7.5	5	450	239	65	11.6	71
	After sweet potato	5.8	72.4	5.9	5	485	234	63	12.2	64
	SED	0.08	2.17	ns	0.7	ns	14.5	ns	ns	4.8

[1] SED = standard error of the difference between means (6 df); ns = no statistical difference ($P > 0.05$).

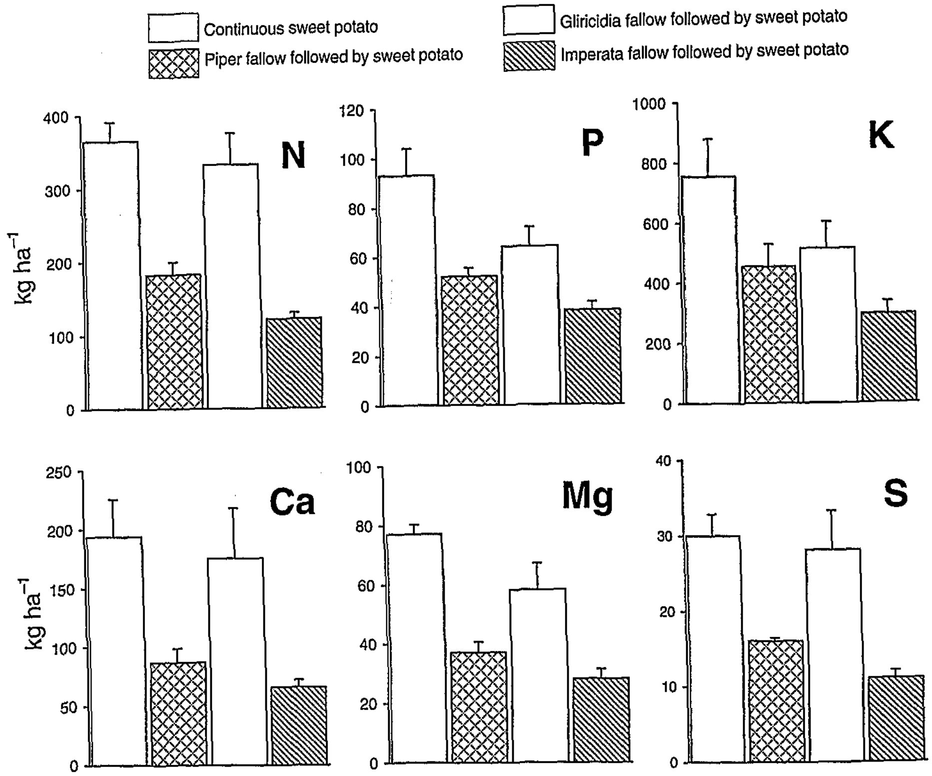

Figure 2. Total nutrient removal (kg ha^{-1}) with fallow and sweet potato biomass after two years (error bar = 1 standard deviation).

Nutrient input and output and change in soil contents

The nutrient input in the continuous sweet potato plots was zero and as a result the difference between input and output was largest for all major nutrients (Table 8). The difference was particularly large for N (–365 kg ha^{-1}) and K (–756 kg ha^{-1}). Differences between the input and output of N, P, K and S were negative for all treatments, but in the case of Ca the difference was positive for piper and for gliricidia followed by two crops of sweet potato. This was due to the high input of Ca by the piper and gliricidia biomass and the relatively low output (removal) by the sweet potato tubers and vines. Also the Mg budget was positive for piper.

Changes in soil nutrient contents were calculated as the difference in nutrient content of the topsoil (0–0.15 m) at the beginning of the experiment and nutrient content two years later (Table 8). Topsoil N contents decreased considerably under piper and under imperata followed by sweet potato. The decrease was much smaller under gliricidia followed by sweet potato and under continuous sweet potato. Changes in soil P contents were only small and ranged from –1.8 to –4.3 kg P ha^{-1} over the two-year period; the largest change in P was found under continuous sweet potato and the

Table 5. Bulk density ($t\ m^{-3} \pm 1$ SD[1]) at two soil depths under continuous sweet potato cropping, and before and after a one-year fallow with *Piper aduncum*, *Gliricidia sepium* or *Imperata cylindrica* followed by two seasons of sweet potato.

Cropping system	Sampling time	Soil depth	
		0–0.05 m	0.10–0.15 m
Continuous sweet potato	Before 1st planting	0.67 ± 0.10	0.62 ± 0.06
	After two seasons (1 year)	0.68 ± 0.08	0.77 ± 0.08
	After four seasons (2 years)	0.64 ± 0.06	0.75 ± 0.08
P. aduncum fallow followed by two seasons sweet potato (1 year)	Before the fallow	0.61 ± 0.07	0.71 ± 0.08
	After the fallow (1 year)	0.70 ± 0.10	0.81 ± 0.06
	After two seasons sweet potato (1 year)	0.60 ± 0.05	0.71 ± 0.04
G. sepium fallow followed by two seasons sweet potato (1 year)	Before the fallow	0.57 ± 0.05	0.64 ± 0.05
	After the fallow (1 year)	0.64 ± 0.06	0.75 ± 0.03
	After two seasons sweet potato (1 year)	0.61 ± 0.03	0.66 ± 0.01
I. cylindrica fallow followed by two seasons sweet potato (1 year)	Before the fallow	0.59 nd[2]	0.74 nd
	After the fallow (1 year)	0.67 ± 0.04	0.81 ± 0.06
	After two seasons sweet potato (1 year)	0.62 ± 0.09	0.56 ± 0.10

[1] SD = standard deviation.

[2] nd = not determined: insufficient data.

smallest for gliricidia and imperata followed by sweet potato. The decrease in total soil K contents was largest in the soils under continuous sweet potato and lowest under imperata followed by sweet potato. The decrease in soil K contents under piper and gliricidia fallow was similar. Piper biomass returned enough K for about one season of sweet potato whereas the K in the gliricidia and imperata crops was highly insufficient for one or more crops of sweet potato. Calcium contents decreased considerably in all four treatments but the decrease was largest for the imperata followed by sweet potato and for the continuous sweet potato crop.

The relation between nutrient budgets and changes in topsoil contents differs considerably for different nutrients. It appears that much more N was lost from the topsoil under piper and imperata fallow followed by sweet potato than could be explained by the nutrient budget. On the other hand, the P and K budget was much more negative for all treatments than the difference in soil P and K contents. Changes in topsoil Ca contents were much larger than could be explained by the nutrient budg-

Table 6. Volumetric soil moisture contents (m^3 m^{-3}) under continuous sweet potato, and in sweet potato preceded by a one-year fallow of *Piper aduncum*, *Gliricidia sepium* or *Imperata cylindrica*.

Sampling time[1]	Sampling depth	Continuous sweet potato	Sweet potato after one year fallow with:			SED[2]
			P. aduncum	*G. sepium*	*I. cylindrica*	
(weeks)	(m)					
–1	0–0.05	0.35	0.27	0.33	0.31	0.01
	0.10–0.15	0.37	0.30	0.39	0.33	0.03
12	0–0.05	0.42	0.43	0.44	0.47	0.01
	0.10–0.15	0.42	0.42	0.46	0.46	0.02
24	0–0.05	0.39	0.40	0.42	0.42	0.03
	0.10–0.15	0.41	0.40	0.38	0.41	0.03

[1] Weeks after fallow vegetation was slashed and sweet potato was planted.

[2] SED = standard error of the difference between means (9 df).

et. The positive Mg budget also resulted in net increases in soil Mg contents in the piper and imperata fallow followed by two seasons of sweet potato.

Discussion

Considerable differences were found in nutrient input by the fallow crops, in the effects of the fallows on sweet potato, and in changes in soil chemical and physical properties. Several of these factors interact and this discussion focuses on differences and similarities between these factors. Although there is a growing body of literature on the effects of (improved) fallows in the tropics including gliricidia, most studies have focused on grain crops (e.g. Hartemink *et al.*, 2000c; Juo *et al.*, 1995; Silva-Forsberg & Fearnside, 1997; Zaharah *et al.*, 1999) or on nutrient recovery from fallow mulch under laboratory conditions (e.g. Cadisch *et al.*, 1998), which hampers comparisons with the present study in which the fallow effects on a tuber crop under field conditions were studied.

Nutrient input and sweet potato yields

Nutrient input by aboveground biomass of the woody fallows (piper and gliricidia) was large in comparison with other studies on high base status soils in the humid tropics (Szott *et al.*, 1999). In the first cropping season, the fallows had a significant effect on sweet potato tuber and vine yield. Sweet potato yields were significantly higher after piper than after gliricidia. This is likely caused by the high K input of the piper

Table 7. Nutrient removal (kg ha^{-1} ± 1 SD[1]) under continuous sweet potato, and in one-year old fallows of *Piper aduncum*, *Gliricidia sepium* or *Imperata cylindrica* followed by two seasons of sweet potato. Removal includes nutrients in the marketable and non-marketable tubers and in the vine biomass.

Cropping system	Season	Nutrients					
		N	P	K	Ca	Mg	S
Continuous sweet potato	1997 – 1st season	117 ± 10.4	33 ± 3.3	298 ± 46.2	66 ± 11.9	26 ± 2.4	9 ± 0.4
	1997 – 2nd season	69 ± 3.8	13 ± 3.7	120 ± 29.4	35 ± 8.3	14 ± 1.6	4 ± 0.6
	1998 – 3rd season	95 ± 10.4	25 ± 3.9	164 ± 55.6	47 ± 12.0	18 ± 0.6	8 ± 1.4
	1998 – 4th season	84 ± 20.5	22 ± 5.6	174 ± 64.6	46 ± 11.0	19 ± 3.7	9 ± 2.0
P. aduncum fallow followed by two seasons sweet potato (1 year)	Fallow[2]	23 ± 2.8	7 ± 0.6	92 ± 7.9	10 ± 1.6	5 ± 1.4	1 ± 0.1
	1998 – 1st season	90 ± 10.2	26 ± 2.0	202 ± 47.0	38 ± 9.7	16 ± 2.6	8 ± 0.8
	1998 – 2nd season	69 ± 8.4	19 ± 1.8	159 ± 23.3	39 ± 5.5	16 ± 2.2	7 ± 0.3
G. sepium fallow followed by two seasons sweet potato (1 year)	Fallow[2]	164 ± 24.0	24 ± 4.5	159 ± 11.3	90 ± 22.4	23 ± 3.5	13 ± 2.7
	1998 – 1st season	83 ± 14.8	22 ± 4.7	195 ± 55.3	40 ± 18.0	16 ± 5.0	7 ± 1.7
	1998 – 2nd season	84 ± 19.4	18 ± 1.5	159 ± 30.6	45 ± 11.9	19 ± 4.9	8 ± 1.4
I. cylindrica fallow followed by two seasons sweet potato (1 year)	Fallow[3]	0	0	0	0	0	0
	1998 – 1st season	60 ± 7.9	20 ± 2.9	137 ± 19.0	34 ± 1.3	14 ± 2.3	5 ± 0.7
	1998 – 2nd season	61 ± 8.0	18 ± 1.1	156 ± 18.6	32 ± 4.7	14 ± 2.5	6 ± 0.2

[1] SD = standard deviation.

[2] Nutrients removed in the woody biomass (stems) when the fallow vegetation was slashed.

[3] No nutrients removed: all nutrients returned to the soil.

Table 8. Nutrient transfer and output (kg ha^{-1}) under continuous sweet potato (four seasons), and after a one-year fallow of *Piper aduncum*, *Gliricidia sepium* or *Imperata cylindrica* followed by two seasons of sweet potato. Total period: two years.

Nutrient		Cropping system			
		Continuous sweet potato	*P. aduncum* – sweet potato	*G. sepium* – sweet potato	*I. cylindrica* – sweet potato
N	Transfer[1]	0	97	192	76
	Output[2]	365	182	331	121
	Difference	–365	–85	–139	–45
	Change topsoil content[3]	–209	–708	–211	–833
P	Transfer	0	14	12	12
	Output	93	52	64	38
	Difference	–93	–38	–52	–26
	Change topsoil content	–4.3	–2.6	–1.8	–1.9
K	Transfer	0	206	89	89
	Output	756	453	513	293
	Difference	–756	–247	–424	–204
	Change topsoil content	–148	–94	–90	–33
Ca	Transfer	0	147	222	56
	Output	194	87	175	66
	Difference	–194	60	47	–10
	Change topsoil content	–843	–698	–426	–950
Mg	Transfer	0	40	41	29
	Output	77	37	58	28
	Difference	–77	3	–17	1
	Change topsoil content	–26	15	–28	16
S	Transfer	0	9	12	4
	Output	30	16	28	11
	Difference	–30	–7	–16	–7
	Change topsoil content	nd[4]	nd	nd	nd

[1] Transfer = nutrients returned with the leaves, branches and litter from *P. aduncum* or from *G. sepium*, or with the leaves from *I. cylindrica* (from Table 1).

[2] Output = nutrients removed with sweet potato tubers and vines (4 seasons for continuous cropping; 2 seasons for plots following a fallow crop); nutrients removed with *P. aduncum* stems and with sweet potato tubers and vines; nutrients removed with *G. sepium* stems and with sweet potato tubers and vines (from Table 7).

[3] Change topsoil content = calculated from difference in soil nutrient contents (0–0.15 m) prior to the experiment and two years later (from Tables 4 and 5).

[4] nd = no data available.

biomass of which 112 kg ha^{-1} was released within eight weeks (Hartemink & O'Sullivan, 2001). Sweet potato has a high demand for K (George *et al.*, 2002; Nicholaides *et al.*, 1985) and K influences tuber yield via increased dry matter allocation to the tubers and an increase in number of tubers per plant (Bourke, 1985a).

Sweet potato has generally a low demand for P (Hahn & Hozyo, 1984) and as the soils had fair amounts of available P, the recycling of P by the fallow crop had possibly little effect on sweet potato yield. Hartemink *et al.* (2000b) sampled sweet potato leaves under continuous sweet potato for four seasons at the same site and found that P levels were at least 50% above the critical level and no decreasing trend occurred over time. Also pot trials with soils from the same site showed no response to P. This suggests that P is not limiting sweet potato production.

Gliricidia fallows added large amounts of N and the N input was two times larger than that of piper and imperata fallows. Nitrogen influences sweet potato yield by increasing leaf area duration, which in turn increases mean tuber weight and thus tuber yield (Bourke, 1985a) but too much N reduces tuber yields (Hill *et al.*, 1990; Marti & Mills, 2002). The high N input by the gliricidia resulted in high vine production and a lower harvest index, which may explain the lower yields after gliricidia fallow in comparison with the other fallows. The lower yield may also be related to the allelopathic compounds of the gliricidia leaves. Ramakoorthy & Paliwal (1993) have shown that applications of 4 to 12 t ha^{-1} of gliricidia leaf mulch effectively controlled weeds whereas Alan & Barrantes (1998) showed that extracts from gliricidia leaves drastically reduced the germination of weed species including *Ipomoea* sp. It is hard to quantify whether allelopathic effects affected the sweet potato yield although the polyphenolic contents of the gliricidia leaves were indeed significantly higher than in piper or imperata (Hartemink & O'Sullivan, 2001). Phenolic compounds have been reported to possess allelopathic activities (Inderjit & Keating, 1999).

Sweet potato after imperata produced significantly less vine biomass because of the thick layer of imperata leaves on the soil hindering the spreading of vines. Imperata leaves had high C/N ratios and decomposed slowly, which kept the soils more moist and also immobilized about 18 kg N ha^{-1} during the first cropping season after the fallow (Hartemink & O'Sullivan, 2001). The reduced vine biomass production had no significant effect on sweet potato tuber yield despite the fact that vine and tuber yields are often inversely related (Enyi, 1977). In many parts of the humid tropics imperata is known to reduce crop yields (Chikoye *et al.*, 2000; Santoso *et al.*, 1997) and Kamara & Lahai (1997) found a significant yield reduction of sweet potato when more than 10 t ha^{-1} imperata biomass was applied. This was attributed to the high C/N ratio of the mulch and the phytotoxic properties of the imperata biomass (Kamara & Lahai, 1997). Ngiumbo & Balasubramanian (1992) found that burning of the imperata biomass increased yield. Farmers in the experimental area do not burn the fallow debris but burning enhances the bioavailability of nutrients (Giardina *et al.*, 2000) and the burned mulch dries the soil, which could be an advantage under the prevailing wet conditions.

In the second season after the fallow, there was no difference between the treatments. Residual benefits of fallows on crop yields usually last for one or two cropping seasons only (Buresh & Cooper, 1999; Szott *et al.*, 1999). The absence of a response in the second season of this experiment may be related to the rapid mineralization of nutrients in the fallow mulch during the first season (Hartemink & O'Sullivan, 2001). On the whole, sweet potato yields were higher in the second season, which is likely due to the fact that there was 317 mm less rain than in the first season (Figure 1). In the experimental area it was found that in wetter seasons sweet potato yields are significantly reduced regardless of the cropping history of the soil (Hartemink *et al.*, 2000b). Although high rainfall is very beneficial for the biomass and nutrient accumulation of *Piper aduncum* (Hartemink, 2001), it is detrimental during tuber initiation of sweet potato (Gollifer, 1980; Hahn & Hozyo, 1984). Piper fallows significantly reduced soil moisture (Table 7) and this effect lasted for some time after the piper fallow was slashed and sweet potato was planted. This probably is favourable for tuber initiation after piper fallows. The exact relation between soil moisture content and tuber initiation and yields remains to be quantified but this experiment has shown that there may be linkages.

Fallow and sweet potato effects on the soil

Both the fallow and sweet potato crop affected soil chemical and physical properties. During the fallow period a small increase was found in soil organic C content and total N. It is often found, however, that organic C decreases in the first years of a fallow and increases thereafter (Szott *et al.*, 1999). During sweet potato cropping, organic C slightly decreased, which is commonly found for short-term fallows on high-base status soils (Juo *et al.*, 1995; Roder *et al.*, 1997). The soils acidified significantly during the fallow period and the pH further decreased during sweet potato cropping. Although the total changes in pH are considerable, the high-base status of these soils and the fact that sweet potato tolerates a wide range of soil reactions (O'Sullivan *et al.*, 1997) implies little effect on sweet potato production. Exchangeable K significantly decreased during the piper fallow and slightly increased after the piper fallow was slashed, which is in accordance with the high uptake of K by piper and the rapid release of K in the piper biomass.

Changes in soil bulk density were the same under the three fallows: an increase of about 13% during the one-year fallow period. After two crops of sweet potato, bulk density decreased in the previously fallowed plots due to the forking required to harvest the tubers. Under continuous sweet potato cropping, bulk density gradually decreased due to the forking. The soils at the experimental site have low bulk densities and the slight increase during the fallow and the decrease during sweet potato cropping have probably no effect on root or tuber growth. However, bulk density affects mass nutrient balances (Table 9) and also affects soil water storage. Differences in volumetric soil moisture contents differed between the fallows. Soil moisture contents under sweet potato after imperata were highest due to the undecomposed imperata mulch layer. Stephens (1967) also found higher soil moisture contents after imperata fallows than in continuously cropped sweet potato plots because in the former rainfall was accepted more readily.

Nutrient budgets

The long-term sustainability of fallow systems on high base status soils depends on the size of nutrient stocks and the magnitude of net nutrient loss during each crop-fallow cycle (Szott *et al.*, 1999). The nutrient budgets (Table 8) show that continuous sweet potato had the most negative nutrient budget because there was no input. These budgets have some limitations as only nutrients in the 0–0.15 m soil horizon and extractable P and cations were measured. Organic C and total N are total figures but P is extracted by bicarbonate and Ca, Mg and K by NH_4-acetate so P and cations are a fraction of the total amounts present in the soil. On the other hand, the data give a fair quantification of the amounts of nutrients that are potentially available for crop production. As soil depth is limited at the experimental site and most roots were found in the top 0.2 m, deep capture of nutrients, which is important in many fallow systems (Hartemink *et al.*, 2000c), 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.

None of the three fallows (piper, gliricidia and imperata) added sufficient amounts of N, P and K for two consecutive seasons of sweet potato. Although there is some difference between the fallows, the high nutrient demand of sweet potato seems to allow for only one crop after the fallow. The woody fallows had more favourable Ca and Mg budgets than the imperata fallow. As the soils are high in exchangeable Ca and Mg and sweet potato has a relatively low demand for these nutrients the favourable Ca and Mg budgets of woody fallow have limited value.

The major function of fallows is to recycle and conserve nutrients rather than to cause net increases in ecosystem nutrient stocks (Buresh & Cooper, 1999). Gliricidia and piper fallow recycled larger amounts of nutrients than the imperata fallow. The first two produced more biomass than the imperata fallows (Table 4). The larger amounts of nutrients recycled in the fallow-crop system may induce greater losses and some idea on the amount of losses can be obtained by comparing the nutrient budgets with the changes in soil nutrient contents. More N and Ca were lost from the soil than could be explained by the input-output budgets. In the budgets, only input by the aboveground fallow biomass and output by sweet potato vines and tubers and piper and gliricidia wood were considered. Nutrient output by leaching, volatilization, denitrification or soil erosion was not quantified. At a nearby site, Sayok & Hartemink (1998) showed that soil erosion under sweet potato on a 58% slope was less than 4 t soil ha^{-1} $year^{-1}$,which is a very low erosion rate. As the experiment described in this paper was at a slope of less than 2%, nutrient losses by soil erosion are therefore negligible. It is likely that leaching losses were high and this has been reported for other experiments with sweet potato in the humid tropics (Islam *et al.*, 1994), which explains the low N use efficiency that is often found in sweet potato field experiments (Hartemink *et al.*, 2000a).

Conclusions

The long-term sustainability of the different fallow systems can be appraised in different ways; for the farmers tuber yield and useful products of the fallow (wood) are important factors whereas nutrient budgets and changes in soil nutrient contents determine the long-term productivity of the land. Short-term fallows of piper gave higher sweet potato yields than short-term gliricidia fallows but the effects lasted only one season. Gliricidia fallows produced three times more wood, which is an advantage in areas where firewood is scarce. These short-term fallow systems are insufficiently capable to compensate for the high nutrient removal during the consecutive cropping season and possibly the high nutrient losses during the cropping period.

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References

Alan, E. & U. Barrantes, 1998. Efecto alelopático del madero negro (*Gliricidia sepium*) en la germinación y crecimiento inicial de algunas malezas tropicales. *Turrialba* 38: 271–278.

Allen, B.J., R.M. Bourke & R.L. Hide, 1995. The sustainability of Papua New Guinea agricultural systems: the conceptual background. *Global Environmental Change* 5: 297–312.

Bellamy, J.A. & J.R. McAlpine, 1995. Papua New Guinea Inventory of Natural Resources, Population Distribution and Land Use: Handbook (2nd edition). Australian Agency for International Development, Canberra, 149 pp.

Bleeker, P., 1983. Soils of Papua New Guinea Australian. National University Press, Canberra, 352 pp.

Bourke, R.M., 1985a. Influence of nitrogen and potassium fertilizer on growth of sweet potato (*Ipomoea batatas*) in Papua New Guinea. *Field Crops Research* 12: 363–375.

Bourke, R.M., 1985b. Sweet potato (*Ipomoea batatas*) production and research in Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries* 33: 89–108.

Brook, R.M., 1999. Interactions between leguminous hedgerows and a sweet potato intercrop in Papua New Guinea. *Der Tropenlandwirt* 100: 133–146.

Buresh, R.J. & P.J.M. Cooper, 1999. The science and practice of short-term improved fallows: symposium synthesis and recommendations. *Agroforestry Systems* 47: 345–356.

Cadisch, G., E. Handayanto, C. Malama, F. Seyni & K.E. Giller, 1998. N recovery from legume prunings and priming effects are governed by the residue quality. *Plant and Soil* 205: 125–134.

Chikoye, D., V.M. Manyong & F. Ekeleme, 2000. Characteristics of speargrass (*Imperata cylindrica*) dominated fields in West Africa: crops, soil properties, farmer perceptions and management strategies. *Crop Protection* 19: 484–487.

Enyi, B.A.C., 1977. Analysis of growth and tuber yield in sweet potato (*Ipomoea batatas*) cultivars. *Journal of Agricultural Science* 88: 421–430.

Freyne, D.F. & J.R. McAlpine, 1987. Land clearing and development in Papua New Guinea. In: R. Lal, M. Nelson, H.W. Scharpenseel & M. Sudjadi (Eds), Tropical Land Clearing for Sustainable Agriculture. Proceedings of an IBSRAM inaugural workshop. International Board for Soil Research and Management (IBSRAM), Bangkok, pp. 153–163.

George, M.S., G.Q. Lu & W.J. Zhou, 2002. Genotypic variation for potassium uptake and utilization efficiency in sweet potato (*Ipomoea batatas* L.). *Field Crops Research* 77: 7–15.

Giardina, C.P., R.L. Sanford, I.C. Dockersmith & V.J. Jaramillo, 2000. The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil* 220: 247–260.

Gollifer, D.E., 1980. A time of planting trial with sweet potatoes. *Tropical Agriculture* 57: 363–367.

Hahn, S.K. & Y. Hozyo, 1984. Sweet potato. In: P. R. Goldsworthy & N. M. Fisher (Eds), The Physiology of Tropical Field Crops. John Wiley & Sons, New York, pp. 551–567.

Hartemink, A.E., 2001. Biomass and nutrient accumulation of *Piper aduncum* and *Imperata cylindrica* fallows in the humid lowlands of Papua New Guinea. *Forest Ecology and Management* 144: 19–32.

Hartemink, A.E. & R.M. Bourke, 2000. Nutrient deficiencies of agricultural crops in Papua New Guinea. *Outlook on Agriculture* 29: 97–108.

Hartemink, A.E. & J.N. O'Sullivan, 2001. Leaf litter decomposition of *Piper aduncum, Gliricidia sepium* and *Imperata cylindrica* in the humid lowlands of Papua New Guinea. *Plant and Soil* 230: 115–124.

Hartemink, A.E., M. Johnston, J.N. O'Sullivan & S. Poloma, 2000a. Nitrogen use efficiency of taro and sweet potato in the humid lowlands of Papua New Guinea. *Agriculture, Ecosystems & Environment* 79: 271–280.

Hartemink, A.E., S. Poloma, M. Maino, K.S. Powell, J. Egenae & J.N. O'Sullivan, 2000b. Yield decline of sweet potato in the humid lowlands of Papua New Guinea. *Agriculture, Ecosystems & Environment* 79: 259–269.

Hartemink, A.E., R.J. Buresh, P.M. Van Bodegom, A.R. Braun, B. Jama & B.H. Janssen, 2000c. Inorganic nitrogen dynamics in fallows and maize on an Oxisol and Alfisol in Kenya. *Geoderma* 98: 11–33.

Hill, W.A., H. Dodo, S.K. Hahn, K. Mulongoy & S.O. Adeyeye, 1990. Sweet potato root and biomass production with and without nitrogen fertilization. *Agronomy Journal* 82: 1120–1122.

Inderjit & K.I. Keating, 1999. Allelopathy: Principles, procedures, processes, and promises for biological control. *Advances in Agronomy* 67: 141–231.

Islam, T., I. Hasegawa, K. Ganno, N. Kihou & T. Momonoki, 1994. Vinyl-film mulch: a practice for sweet potato (*Ipomoea batatas* Lam. var. Edulis Makino) cultivation to reduce nitrate leaching. *Agricultural Water Management* 26: 1–11.

Juo, A.S.R., K. Franzluebbers, A. Dabiri & B. Ikhile, 1995. Changes in soil properties during long-term fallow and continuous cultivation after forest clearing in Nigeria. *Agriculture, Ecosystems & Environment* 56: 9–18.

Kamara, A.Y. & M.T. Lahai, 1997. Differential response of sweet potato (*Ipomoea batatas*) to green manuring with elephant grass (*Pennisetum purpureum*) and spear grass (*Imperata cylindrica*) on a Ferralitic soil in Sierra Leone. *Tropenlandwirt* 98: 229–235.

Levett, M.P., 1993. The effects of methods of planting cuttings of sweet potato [*Ipomoea batatas* (L) Lam] on yield. *Tropical Agriculture* 70: 110–115.

Louman, B. & A.E. Hartemink, 1998. Sweet potato production in hedgerow intercropping systems in the lowlands of Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries* 41: 91–98.

Marti, H.R. & A.H. Mills, 2002. Nitrogen and potassium nutrition affect yield, dry weight partitioning, and nutrient-use efficiency of sweet potato. *Communications in Soil Science and Plant Analysis* 33: 287–301.

Ngiumbo, K.A.B. & V. Balasubramanian, 1992. Effect of fallow and residue management practises on biomass production, weed suppression and soil productivity. In: K. Mulongoy, M. Gueye & D.S.C. Spencer (Eds), Biological Nitrogen Fixation and Sustainability of Tropical Agriculture. John Wiley, Chichester, pp. 463–473.

Nicholaides, J.J., H.F. Chancy, H.J. Mascagni, L.G. Wilson & D.W. Eaddy, 1985. Sweet potato response to K and P fertilization. *Agronomy Journal* 77: 466–470.

O'Sullivan, J.N., C.J. Asher & F.P.C. Blamey. 1997. Nutrient Disorders of Sweet Potato. Monograph No 48, Australian Centre for International Agricultural Research (ACIAR), Canberra, 136 pp.

Powell, K.S., A.E. Hartemink, J.F. Egenae, C. Walo & S. Poloma, 2001. Sweet potato weevil (*Cylas formicarius*) incidence in the humid lowlands of PNG. In: R.M. Bourke, M.G. Allen & J.G. Salisbury (Eds), Food Security in Papua New Guinea. Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 736–745.

Ramakoorthy, M. & K. Paliwal, 1993. Allelopathic compounds in leaves of *Gliricidia sepium* (Jacq.) Kunth ex Walp. and its effect on *Sorghum vulgare* L. *Journal of Chemical Ecology* 19: 1691–1701.

Roder, W., S. Phengchanh & S. Maniphone, 1997. Dynamics of soil and vegetation during crop and fallow period in slash-and-burn fields of northern Laos. *Geoderma* 76: 131–144.

Rogers, H.R. & A.E. Hartemink, 2000. Soil seed bank and growth rates of an invasive species, *Piper aduncum*, in the lowlands of Papua New Guinea. *Journal of Tropical Ecology* 16: 243–251.

Sanchez, P.A., 1999. Improved fallows come of age in the tropics. *Agroforestry Systems* 47: 3–12.

Sanchez, P.A., R.J. Buresh & R.R.B. Leakey, 1997. Trees, soils, and food security. In: D. J. Greenland, P.J. Gregory & P.H. Nye (Eds), Land Resources: on the Edge of the Malthusian Precipice? *Philosophical Transactions of the Royal Society of London* Series B: 949–961.

Santoso, D., S. Adiningsih, E. Mutert, T. Fairhurst & M. Van Noordwijk, 1997. Soil fertility management for reclamation of imperata grasslands by smallholder agroforestry. *Agroforestry Systems* 36: 181–202.

Saulei, S.M. & M.D. Swaine, 1988. Rain forest seed dynamics during succession at Gogol, Papua New Guinea. *Journal of Ecology* 76: 1133–1152.

Sayok, A.K. & A.E. Hartemink, 1998. Erosion and soil fertility changes under leucaena intercropped with sweet potato in the lowlands of Papua New Guinea. *Papua New Guinea Journal of Agriculture, Forestry and Fisheries* 41: 85–90.

Silva-Forsberg, M.C. & P.M. Fearnside, 1997. Brazilian Amazonian *caboclo* agriculture: effect of fallow period on maize yield. *Forest Ecology and Management* 97: 283–291.

Simons, A.J. & J.L. Stewart, 1994. *Gliricidia sepium* - a multipurpose forage tree legume. In: R. C. Gutteridge & H. M. Shelton (Eds), Forage Tree Legumes in Tropical Agriculture. CAB International, Wallingford, pp. 30–48.

Stephens, D., 1967. Effects of grass fallow treatment in restoring fertility of Buganda clay loam in South Uganda. *Journal of Agricultural Science* 68: 391–403.

Szott, L.T., C.A. Palm & R.J. Buresh, 1999. Ecosystem fertility and fallow function in the humid and subhumid tropics. *Agroforestry Systems* 47: 163–196.

Walker, D.W., T.J. Hubbel & J.E. Sedberry, 1989. Influence of decaying sweet potato crop residues on nutrient uptake of sweet potato plants. *Agriculture, Ecosystems and Environment* 26: 45–52.

Young, A., 1997. Agroforestry for Soil Management (2nd edition). CAB International, Wallingford, 320 pp.

Zaharah, A.R., A.R. Bah, N.K. Mwange, P. Kathuli & P. Juma, 1999. Management of Gliricidia (*Gliricidia sepium*) residues for improved sweet corn yield in an ultisol. *Nutrient Cycling in Agroecosystems* 54: 31–39.