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Site-and watershed-level assessment of nutrient dynamics under shifting cultivation in eastern Madagascar

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Abstract

Nutrient depletion is an important limiting factor for agricultural sustainability in shifting cultivation systems. This paper presents a case study examining nutrient dynamics for a hillrice-fallow system located on the eastern escarpment of Madagascar. A nutrient assessment was carried out, measuring total C, N, P, K, Ca and Mg concentrations in phytomass, ashes and harvests and total C and N, exchangeable K, Ca and Mg and available P concentrations in topsoils, soil loss material and river discharges. At representative slash-and-burn sites, the soil-pool of P and K increased from 100% beneath 5-year-old fallow vegetation to 166% and 126% at harvest, but Ca and Mg decreased. Comparisons between fallow and burnt fields showed that 95–98% of phytomass-fixed and 22–24% of soil-fixed C and N were lost by burning. Paddy at harvest only contained 1–7% of the nutrients in the burnt phytomass of the previous stand. Nutrients regenerated rapidly in the fallow vegetation, which after 1 year contained already 36–57% of the previous phytomass pool, whereas topsoil nutrient concentrations started to increase only after 3–5 years of fallow. The long-term nutrient depletion was studied by comparing nutrient stocks at sites and watersheds, which were characterised by increasing levels of degradation. The topsoil cation content increased during the early stages of shifting cultivation, but under long-term shifting cultivation, the soil nutrients fell to approximately 2/3 of the initial stock. The nutrient stocks of the most degraded vegetation unit (grassland) was merely 1.1–6.5% of the nutrient stocks in the rainforest. Finally, the nutrient stocks in a forested and a degraded watershed were calculated and compared. The established nutrient balances showed, that the dynamics and the depletion depend greatly on the spatio-temporal scale of observation, on the topography of the sites and on the type of nutrients.

Keywords: Madagascar; Nutrient balance; Nutrient depletion; Shifting cultivation

1. Introduction

Since 1960 with the work of Nye and Greenland, 1960, important research efforts have been focused on nutrient depletion in slash-and-burn systems. Sanchez (1996) recorded that shifting cultivation, practised by 300–500 million farmers, was responsible for the bulk of rainforest clearing, which totals about 10 million hectares per year worldwide. In a response to these problems, detailed studies and reviews of the impacts of slash-and-burn agriculture on fallow degradation, soil fertility and yields have been numerous in recent decades (Ewel et al., 1981; Kyuma et al., 1985; Lal et al., 1986; Andriesse and Schelhaas, 1987a, b; Ramakrishnan, 1992; Sanchez and Hailu, 1996).

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Yet, most slash-and-burn farmers are still convinced of the relative advantages presented by this technique. These advantages include the fact that slashing and burning removes weeds from the topsoil and keeps predators away. Moreover, the ashes serve as an important fertilizer (Weischet and Caviedes, 1993).

On the eastern escarpment of Madagascar, hillrice-growing following slash-and-burn (*tavy*) is the prevailing agricultural method. Environmental degradation represents a growing obstacle to sustainable agricultural production. Presently, *tavy* is raising wide concern among conservationists, as it threatens the remaining endemic rainforest harbouring a richness in biodiversity.

These issues triggered a systemic research program in the Beforona region, aimed at diagnosing the prevailing constraints as well as identifying potential approaches towards sustainable development.

Insufficient nutrient management is supposed to be a major constraint in shifting cultivation systems. However, on the eastern escarpment of Madagascar, knowledge of the stocks, the balances and the flows of nutrients is widely lacking. This study is concerned with nutrient depletion at three spatio-temporal scales, i.e. site-level during one slash-and burn cycle, site-level under long-term cultivation and the watershed-level.

2. Materials and methods

2.1. Area description

The study area of Beforona represents a typical transect of the central eastern escarpment of Madagascar. The western part is composed of mountains (750–1200 m) and covered by primary rainforest. The adjacent zone towards the east has a hilly relief (350–750 m) covered by various types of secondary vegetation (*savoka*). At the extreme east (150–350 m), the hills are partly covered by grasslands, indicating the advanced degradation of the soils and biodiversity. The humid-tropical climate provides an annual rainfall of 2000–3500 mm. The average temperature is 24°C at sea level, and 19–20°C at 900 m.

The local population belongs to the ethnic group called *Betsimisaraka*, who venerate their ancestors and are therefore devoted to their culture of slash-and-burn agriculture. The population density is approximately 26 persons km^{-2} near the forests and 19 persons km^{-2} in the degraded zones and population growth is 2.7%, which is the national average. Mainly on slopes, the hillrice and fallow surfaces occupy three quarters of the study area, and mixed banana, coffee and fruit trees are cultivated on incised valley floors. The few irrigated ricefields are only extensively cultivated. Most recently, cash-crops like banana, coffee and ginger have been quickly developing.

2.2. Research sites and watersheds

Following a slash-and-burn cycle, topsoils were analyzed on 22 farmers fields, ranging from degraded plots to fertile plots near the forest border. On 11 of these fields, the preceding fallow vegetation, the ashes, the harvest and the rice straws were measured by Ravoavy (1996). Regeneration was studied on 76 plots, classified according to their duration of fallow (1–5 and 6–10 years) with topsoil, litter and phytomass analysis.

The analysis of the long-term nutrient depletion was based on the results collected from 58 sites under fallow vegetation in different topographic situations and after different durations of shifting cultivation. Analyses of phytomass, topsoil and their nutrient concentrations have been carried out on each site (Rakotozafy, 1996; Razafintsalama, 1996; Brand and Rakotondranaly, 1997 ; Pfund et al., 1997). The sites were then classified into 5 classes (rainforest, shrub-fallow, mixed fallow, degraded fallow and grassland) representing increasing stages of degradation, as recognized by the farmers.

Two distinct watersheds have been selected to study the long-term effects of shifting cultivation. The watershed of Vohidrazana (946 ha) is at an initial stage for slash-and-burn agriculture, which started 60 years ago. Here, the area still has 85% forest cover and relatively fertile topsoils. The watershed of Salampinga (350 ha) has undergone slash-and-burn agriculture for more than 200 years. This zone now shows advanced stages of degradation with 30% grassland and degraded fallows and only 3% rainforest.

2.3. Cartography

Coloured aerial photographs at 1:10 000 of the Vohidrazana and Salapinga watersheds (November

1992) were used to interpret 12 different vegetation types. This included a preliminary delimitation and interpretation, along with a field verification of the age and type of vegetation (Vololonirainy, 1995). A reclassification into 6 classes (the above five stages along with hillrice-plots) was undertaken. The maps were digitised and the surfaces of the 6 classes analyzed with a Geographical Information System (ArcInfo, Idrisi).

2.4. Nutrient stock in phytomass, paddy and rice-straw

Phytomass was cut close to the ground and sampled with repetitive weighing of phytomass per square meter until a coefficient of variation under 20% was achieved. The samples were divided by species or according to woody parts, non-woody parts and dead phytomass including litter. The dry weight was measured with oven-dried sub-samples of 5 kg. The samples of 5 kg were collected during the weighing of phytomass and dried at 65°C for 48 h. The samples were kept at 5°C and again oven-dried before analysis of sub-samples ranging between 0.5 and 2 g. N was measured using the Kjeldahl method and P was measured by spectrophotometer. K, Ca and Mg were measured using atomic absorption. Total nutrient stocks in the phytomass were calculated by multiplication of the nutrient concentrations with the phytomass. The same method was applied for paddy and rice-straw, which were sampled at harvest, using several quadrats (2 m×2 m) in each field.

2.5. Nutrient stock in ashes

Measuring ashes on slash-and-burn fields is a sensitive issue. The commonly used receptor method did not give reliable results. On fields in eastern Madagascar burning is often incomplete, leaving woody parts and humid litter partly unburnt. The ash-mass reportedly amounted to 5.7% of the previous phytomass (without litter) by almost complete burning, whereas there was a ratio of 14% of the previous phytomass (10% when including litter) resulting from incomplete burning (Messerli, unpublished data). Yet, the sampled fine ashes resulted rather from complete burning, but this did not take into account the unburnt parts of vegetation and litter. Therefore, a rather complete burning was assumed and an ash-weight of 4.5% of the preceding phytomass and litter was estimated for the subsequent balances. The total nutrient stock was calculated by multiplicating the ash-mass with its nutrient concentrations.

2.6. Nutrient stocks in topsoils

Topsoils on slash-and-burn plots were analysed before slashing, after burning, at harvest and under 1, 3 and 5–year old fallow. The mean thickness (20 cm) and bulk-density (1.0 g cm^{-3}) of the topsoil showed only insignificant variation during the slash-and-burn cycle. The mean thickness of the topsoils at the different degradation stages under long-term shifting cultivation decreased from 25 cm under rainforest to 16 cm under grassland, in contrast to the increasing bulk-density (0.91 g cm^{-3}–1.18 g cm^{-3}). The topsoils (0–20 cm) were collected from 10 core samples. Total C (derived from organic matter, colorimeter) and N (Kjeldahl), available P (Bray) and exchangeable K (spectrophotometer), Ca and Mg (colorimeter) were analysed. For the calculation of the total nutrient stocks, topsoils thickness and bulk-density were taken into account.

2.7. Nutrient stocks in eroded soil material and in river discharge

Soil loss was measured on erosion plots (slope: 50–60%; length: 20 m) under rainforest, hillrice, 1–year old fallow and 4–5 year old fallow (Brand and Wilfred, 1997). Runoff was measured after each storm, whereas nutrient concentrations in the remaining topsoil on the plots and in the eroded material were analyzed each month.

Sediment and soluble nutrient concentrations in the river discharge of the two watersheds were continuously sampled during storm-flows and low-flows. The sediments weight were measured after sedimentation and oven-drying and the nutrient concentrations in the sampled riverwater were analyzed. Linear regressions between instantaneous sediment and nutrient charge and water discharge at sampling time were used to estimate the seasonal sediment charge and soluble nutrient charge. The mean nutrient concentrations in the eroded materials on erosion plots were used to calculate the total nutrient stock in the seasonal sediment charge.

2.8. Nutrient balances at site and watershed level

Three nutrient balances (slash-and-burn cropping season at site level; long-term shifting cultivation at site-level; long-term shifting cultivation at watershed level) were established according the method of Stoorvogel and Smaling (1990). Input 1 (mineral fertilizer), input 2 (manure) and input 5 (sedimentation) were assumed to be not relevant. For input 3 (wet deposition) and input 4 (N-fixation) the estimated values for Madagascar (good rainfall area) in Stoorvogel and Smaling (1990) were used. Output 1 (modified from crop residues to fuelwood extraction), output 2 (harvest products) and output 5 (erosion) were measured. Output 4 (gaseous losses) was based on the denitrification values according to Stoorvogel and Smaling (1990) and the measured volatilization losses of C and N through burning. The analyzed system was limited to the aboveground phytomass and the topsoil. Leaching of nutrients from the topsoil to lower soil horizons (output 3) and nutrient capture in lower horizons by deep-rooting plants were not measured. The balance totals (TOTAL) were calculated for the three spatio-temporal scales by comparing the nutrient stocks a) before and after a slash-and-burn season, b) under rainforest and under degraded fallow and c) for a forested and for a degraded watershed. This allowed the calculation of the resulting difference (DIFF), which is supposed to summarize the non-measured in- and outputs like accumulation of C from the atmosphere, N, P, K, Ca and Mg deep capture, leaching to deeper soil horizons and wind and water erosion of ashes.

However, interpretation of the balances was rather difficult because P and cations were analyzed in total concentrations for phytomass but in available and exchangeable fractions for topsoils. Even if the summation of total and exchangeable fractions is a common technique (Ewel et al., 1981; Szott and Palm, 1996), it makes comparisons with nutrient balances elsewhere difficult. Increasing and decreasing pH during slash-and-burn and under long-term degradation modify the available and exchangeable fractions and thus influence the balance. However, it is supposed to have little influence on the significance of the general figures, showing the nutrient losses and flows at different spatio-temporal scales under shifting cultivation.

3. Results and discussion

3.1. Site-level nutrient dynamics during one slash-and-burn cycle

3.1.1. Phytomass and aboveground nutrient concentrations

In the region of Beforona, the mean fallow duration on slash-and-burn plots is 5 years. Table 1 shows the mean phytomass, littermass and nutrient concentration at that stage of fallow. After slashing and during the drying process (September to October), the phytomass decays and provides its first nutrients to the soils. Ewel et al. (1981) recorded important decays for K (33%) and P (31%) during this period, as well as an increase for these elements in the first centimeters of topsoil. The burning of the slashed phytomass provided an estimated 1.4 t ha^{-1} of ashes, which had a 5 – 20 times higher P and cation concentration, a similar N concentration but a lower C concentration than the preceding phytomass. Similar (K, Ca) or somewhat lower (N, P) concentration were found after burning a 12–15-year-old fallow in Sarawak (Andriesse and Schelhaas, 1987b).

Rice grew quickly on traditional *tavy*, but was inhibited by weeds, which had a phytomass of approximately 0.5–1.0 t ha^{-1} after 90 days. Farmers remove weeds from their land generally twice per year, leaving the residues on the site. At harvest, important variations in the phytomasses for rice straws and paddy were measured on 11 *tavy*. Compared with the average values for paddy and rice straw in sub-Saharan Africa (Stoorvogel and Smaling, 1990), similar N and K concentrations in paddy, somewhat lower N and K concentrations in rice straws and more than 10 times lower P concentrations in paddy and rice straws were found.

Besides soil condition, secondary succession depends on the rapid expansion of pioneer species and the neighboring vegetation. During succession, phytomass increased approximately 5 t ha^{-1} yr^{-1}, whereas nutrient concentration generally decreased (Table 1). N, P and K concentrations were particularly

Table 1
Nutrient concentrations in phytomass, ashes, cultures, litter and topsoil (0–20 cm) during one slash-and-burn cycle (mean ± SD)

Nutrient concentration in phytomass, ashes, crop and litter	Ashes (n=11)	Paddy (n=11)	Rice-straw (n=11)	Fallow 1 year (n=12)	Litter 1 year (n=12)	Fallow 3 years (n=13)	Litter 3 years (n=13)	Fallow 5 years (n=15)	Litter 5 years (n=9)
Mass (t/ha)	1.4±1.0[1]	1.1±0.6	3.1±2.0	8.8±4.2	2.8±1.0	14.2±5.5	5.2±3.7	23.7±16.6	8.4±5.7
C (g kg^{-1})	265±134	489±425	522±68	475[2]	475[2]	475[2]	475[2]	475[2]	475[2]
N (g kg^{-1})	6.8±3.1	11.6±2.2	5.4±2.5	8.3±4.4	7.0±2.2	5.8±3.6	5.6±2.4	6.1±2.0	6.0±4.3
P (g kg^{-1})	8.94±4.16	0.53±0.17	0.16±0.05	0.71±0.39	0.23±0.14	0.48±0.18	0.30±0.23	0.52±0.31	0.20±0.11
K (g kg^{-1})	54.3±56.9	3.7±2.5	28.2±7.1	18.9±5.7	3.7±1.3	16.1±7.5	4.8±7.1	14.2±11.0	10.6±14.5
Ca (g kg^{-1})	75.8±46.8	0.1±0.1	0.4±0.2	3.9±3.5	2.8±3.8	3.1±2.7	2.4±2.5	3.7±2.0	1.9±1.7
Mg (g kg^{-1})	25.0±12.7	0.3±0.1	0.9±0.8	3.9±3.1	3.0±3.8	4.5±5.0	3.7±3.2	2.3±2.0	2.4±3.1

Nutrient concentration [in topsoils (0–20 cm)]	After burn (n=22)	During harvest (n=22)	Under fallow 1 year (n=12)	Under fallow 3 years (n=13)	Under fallow 5 years (n=15)
C_{tot} (g kg^{-1})	45.8±12.8	45.1±10.5	46.9±12.7	38.6±17.2	58.4±21.7
N_{tot} (g kg^{-1})	3.7±0.8	n.m.	5.0±1.8	5.1±2.7	4.8±1.1
P_{av} (mg kg^{-1}, Bray)	7.0±2.8	8.6±4.2	10.9±12.8	8.5±4.2	5.2±2.9
K_{ex} (mg kg^{-1})	84±32	54±38	23.4±19.5	27.3±35.1	42.9±27.3
Ca_{ex} (mg kg^{-1})	368±290	460±298	818±738	628±300	614±332
Mg_{ex} (mg kg^{-1})	251±152	240±140	596±363	557±274	322±196

[1] Calculated value (4.5% of 5-year-old phytomass and litter).
[2] Estimated value.
Abbreviations appearing in subscript: tot - total; av - available; ex - exchangeable; n.m. - not measured.

high after the first year of fallow, when figures are compared with 3 and 5 year-old fallow. According to Heller et al. (1993), this fact results from the dilution effect as phytomass growth exceeds nutrient uptake.

During the fallow period, the amount of litter increased from 1.2 –1.6 t ha^{-1} yr^{-1}. The litter production increased with age and represented more than 25% of the above-ground phytomass after 5 years. Nutrient concentration of litter, similar to the vegetation, showed a great variability, especially for exchangeable cations. No distinct evolution in the nutrient concentration of the litter was found, except for K, which was clearly increasing (Table 1).

3.1.2. Nutrient concentration in topsoil

Table 1 shows that slash-and-burn of a 5-year-old fallow resulted in a decrease of the topsoils C concentration by approximately 20%, which is in agreement with the loss of 30% in upper topsoils (0–8 cm) reported by Ewel et al. (1981). These figures indicate that fire affected the organic matter in the first few centimetres of topsoil. After burning, the C concentration decreased generally until the third year of fallow, which can be related to increased decomposition of organic matter under cultivation (Tulaphitak et al., 1985) and low inputs through litter decomposition during the first years of fallow. After 5 years of fallow the topsoils showed a high C concentration, because of increased contributions from litter. Slash-and-burn also reduced topsoil N stock by almost 20%. Ewel et al. (1981) reported a similar loss of 23% N in topsoils (0–3 cm) after burning. N increased during cultivation but decreased slightly during the fallow period. The P concentration in topsoil increased sharply to twice its preceding level during slash-and-burn cultivation and the first year of fallow. This fact showed the important input of P from decaying phytomass and ashes. After the first year of fallow, P concentration decreased until the fifth year of fallow. After burning, K concentration increased considerably as well. Again, these facts indicate the mobility and the rapid transfer of P and K from the ashes to the topsoil, unlike Ca and Mg which showed a relatively

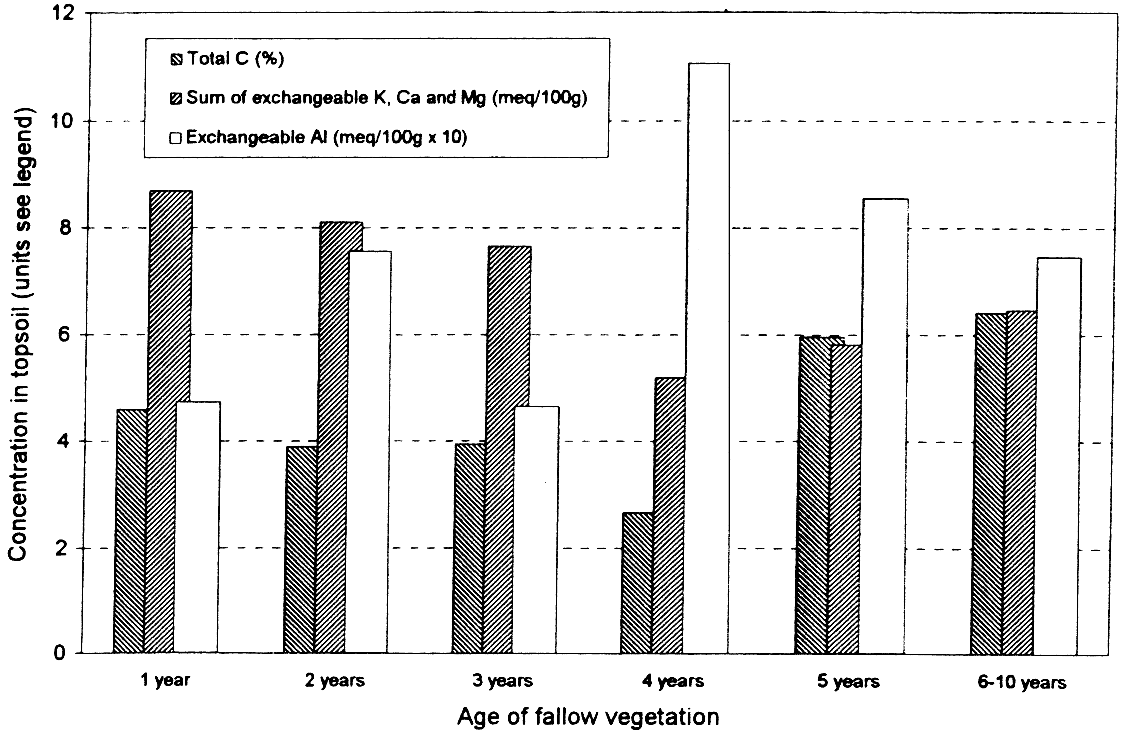

Fig. 1. Evolution of total carbon, sum of exchangeable cations and exchangeable aluminimum concentration in topsoils (0–20 cm) under increasing fallow duration.

low concentration in the topsoil during the growing period. In conclusion, the effect of slash-and-burn on the nutrient status of the topsoil is threefold. C and N decreased sharply, P and K increased temporally but significantly after burning, whereas the topsoil's Ca and Mg showed no positive response after burning. Nevertheless, rice should benefit directly from the Ca and Mg stock in the ashes.

Topsoil fertility regeneration started after 4–5 years of fallow. Fig. 1 shows that during the first 4 years of fallow, the concentration of C and exchangeable cations decreased in the topsoil. From the fourth year onwards, C and cation concentration started to increase, and aluminum toxicity decreased. A similar evolution was noticed by Ramakrishnan (1992) in India. Szott and Palm (1996) reported a decrease of P, K, Ca and Mg stocks, but increasing C and N stocks in the soil from the 17th to the 53rd month of fallow succession. By contrast, Ramakrishnan and Toky (1981) found a continuous decrease of cations, even after 5 years of fallow.

3.1.3. Dynamics of above ground and topsoil nutrient stocks

Fig. 2 shows that 98% C and 95% N were lost through slash-and-burn of a 5-year-old fallow, but its P and Ca stocks remained in the ashes. The decrease of K and Mg from fallow stock to ash stock can partly be explained by the decay of the drying phytomass after slash (Ewel et al., 1981). The nutrients in the ashes are strongly subjected to either wind and water erosion or lost into the topsoil stock. At harvest, the stock of P, Ca and Mg in the remaining rice straw reached negligible quantities, but aboveground C and N stocks were already building up. During the fallow period, the growing phytomass accumulated more and more nutrients, with an increasing proportion found in the litter, whereas the nutrient concentration in the phytomass was decreasing (Table 1).

The evolution of the topsoil nutrient stock during a slash-and-burn cycle is the same as discussed above for nutrient concentration. Approximately 25 t ha^{-1} of C and 2 t ha^{-1} of N were lost from the topsoil from

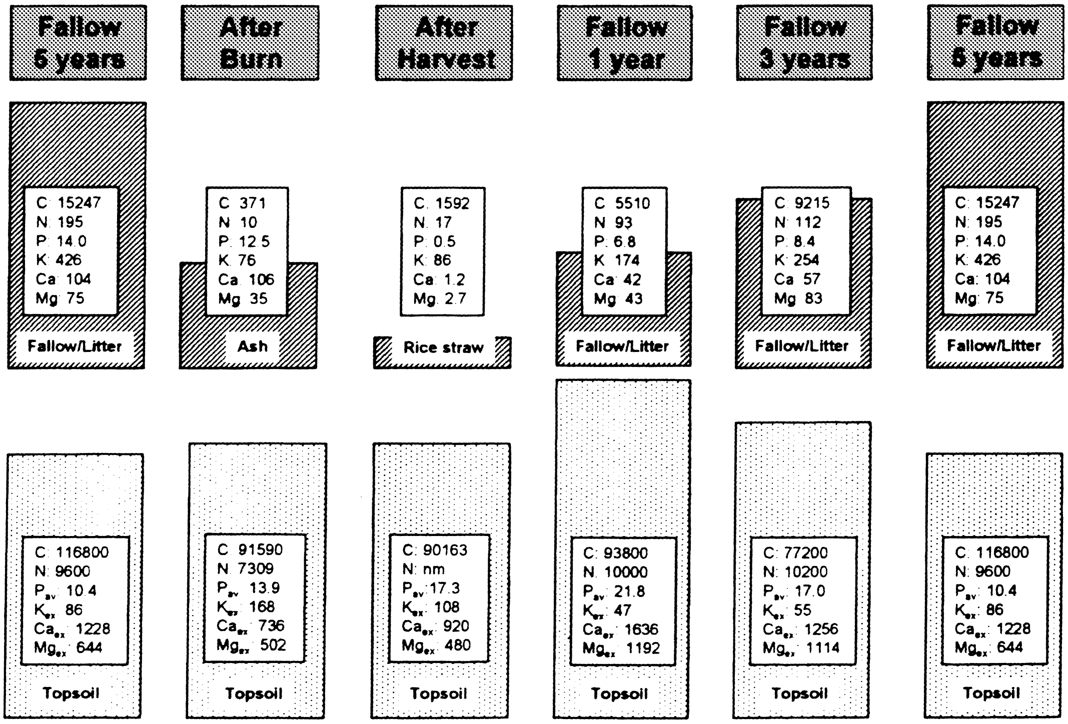

Fig. 2. Mean nutrient stocks (kg/ha) in phytomass and litter, ash, hillrice and topsoil (0–20 cm) during a slash-and-burn cycle. The sizes of the boxes represent the mean proportion of the stock of the six analysed elements as compared with the first stage (Fallow 5 years: 100%).

slash-and-burn. From beneath a 5-year-old fallow until after burning, topsoil P increased by 3.5 kg ha^{-1} and topsoil K increased by 82 kg ha^{-1}. This statement is in agreement with the results of Kang and Juo (1986). At harvest, topsoils showed increases of 66% P and 26% K in comparison with the preceding fallow. During the first years of fallow, the K stock was reduced because of leaching or absorbtion by the young fallow. Although the aboveground P stock decreased during the cropping period and increased during fallow, its topsoil stock increased first and then decreased during the fallow period. This change indicates that, during a slash-and-burn cycle, P was mainly exchanged between the two stocks within the measured system.

The nutrient stocks under 5 year-old fallows were taken as initial and final contents during an average slash-and-burn cycle, as this corresponds to the mean regional fallow duration. However, Fig. 2 should not be misinterpreted in the sense that the nutrient stocks before slash-and-burn regenerate completely during a fallow duration of 5 years.

3.1.4. Nutrient balance during the cropping period of slash-and-burn for hillrice

Table 2 shows the nutrient balance for the growing period of slash-and-burn for hillrice. The great variability in terms of ecological conditions led to the use of average figures of the studied plots without representing the differences between fertile plots and degraded plots. Inputs from mineral fertilizer, organic manure and sedimentation (IN1, IN2, IN5) are not relevant in traditional shifting cultivation on sloping land. Wet deposition (IN3) and biological N-fixation (IN4) were based on cited values for Madagascar (N, P, K: Stoorvogel and Smaling, 1990) and Ghana (Ca, Mg: UNESCO-PNUE, 1979). Removal of crop residues (OUT1) was changed in fuelwood consumption. The average needs per household is approximately 15 kg per day (Ranjatson, unpublished data). Given an average population density of 22.5 persons/km^2, and an average family size of 5 members, the annual fuelwood consumption would be 250 kg ha^{-1}. Fuelwood nutrient concentration was supposed to be the same as for a 5-year-old fallow (Table 1). An average

Table 2
Nutrient balance at site level during the cropping season of hillrice (6 month) after slashing and burning a 5-year-old fallow

	IN3	IN4	OUT1	OUT2	OUT4	OUT5	DIFF	TOTAL
C (kg ha^{-1})	nr	nr	59	538	14 942	629	−24 125	−40 293
N* (kg ha^{-1})	7.7	2.5	0.8	12.8	185	61	–	–
P (kg ha^{-1})	2.9	nr	0.1	0.6	nr	0.2	−8.6	−6.6
K (kg ha^{-1})	6.0	nr	1.8	4.1	nr	nr	−317	−317
Ca (kg ha^{-1})	6.0	nr	0.5	0.1	nr	6.0	−410	−411
Mg (kg ha^{-1})	6.0	nr	0.3	0.3	nr	5.0	−236	−236

IN1,IN2,IN5, are not relevant.
IN3: Wet deposition (N, P, K estimates according to Stoorvogel and Smaling, 1990; Ca, Mg according to UNESCO-PNUE, 1979).
IN4: Biological N-fixation (semi-annual estimates according to Stoorvogel and Smaling, 1990).
OUT1: Fuelwood consumption (250 kg ha^{-1} y^{-1} (Ranjatson, personal communication) with nutrient concentration of a 5 year-old fallow).
OUT2: Harvest products (removal of 1.1 t ha^{-1} of paddy).
OUT3: Leaching (not measured, included in DIFF).
OUT4: Gaseous losses (continuous denitrification according to Stoorvogel and Smaling, 1990; volatilization of 98%C and 95%N of 5 year-old fallow stock).
OUT5: Erosion (14.7 t ha^{-1} soil loss and nutrient concentration in eroded material according to Brand and Wilfred, 1997).
DIFF: Resulting differences in the balance due to C accumulation from the atmosphere, N, P, K, Ca and Mg deep capture, leaching to deeper soil horizons, wind and water erosion of ashes (a part of the differences may result from the limited number of sites, the important spatial variability and imprecise soil analysis).
TOTAL: Net nutrient losses during 6 month of cropping season. Difference between the nutrient stocks in the topsoil and the vegetation under 5 year-old fallow and at harvest.
nr: not relevant or zero.
* N concentration at harvest not measured.

of 1.1 t ha^{-1} of paddy was removed from the fields at harvest (OUT2) and its nutrient concentration is shown in Table 1. Gaseous losses (OUT4) included continuous denitrification (values according to Stoorvogel and Smaling, 1990) and the loss of 98% of C and 95% of N of the nutrient stock in the preceding fallow through burning. Soil erosion during the cropping period of slash-and-burn hillrice (OUT5) was found to be 14.7 t ha^{-1}, with enrichment factors ranging from 0.8 (C) to 3.8 (Ca) (Brand and Wilfred, 1997). The total nutrient loss (TOTAL) represents the difference between the total nutrient stock after 5 years of fallow and during the harvest after one slash-and-burn season. (column 1 and 3 in Fig. 2).

Table 2 shows that the nutrient outputs from fuelwood consumption and harvest removal during the cropping season were relatively minor. Losses through soil erosion were somewhat higher, but these figures are insignificant when compared with the total losses. The highest losses occurred through the burning of the phytomass and the subsequent loss of most volatile C and N. The differences between the presented inputs and outputs and the total losses are very high. It indicates that non-measured nutrient losses like wind and water erosion of the ashes, leaching of nutrients to deeper soil horizons and loss of topsoil C through burning were responsible for the largest part of nutrient losses during the cropping season of slash-and-burn hillrice.

As a comparison to the useful nutrient export in paddy, which contained only 1–7% of nutrient stock from the preceding fallow, the balance shows the significant nutrient loss associated with slash-and-burn agriculture.

3.2. Site-level nutrient dynamics under long-term shifting cultivation

3.2.1. General

Shifting cultivation in a hilly relief causes a large spatial variability of vegetation and soil qualities. Ravoavy (1996); Razafintsalama (1996), Brand (in preparation) and Pfund (in preparation) have studied the complex interrelationship between soil quality, the duration of shifting cultivation, the topographic situation and the characteristics of secondary vegetation. With the objective of quantifying nutrient depletion at site-level under long-term shifting cultivation, the team used a simplified five-stage degradation model. This model was characterized by different types of fallow (rainforest/shrub-fallow/mixed fallow/ degraded fallow/grassland). These stages represent the range of forested land to areas that have been subject to 200–250 years of shifting cultivation. However, only the plots located on upper slopes evolve finally into grassland. On the more favorable footslopes, the degradation can stabilize at an intermediary stage characterized by mixed or degraded fallow.

3.2.2. Phytomass and nutrient concentration in rainforest and fallow vegetation types

The phytomass and nutrient concentration of the rainforest was estimated according to Fassbender (1974), who measured the phytomass of a rainforest in Venezuela, which had about the same height and grew under similar climatic conditions as the research area in Madagascar. The general figures for phytomass of fallow vegetation, which originated from fieldwork by Vololonirainy (1995), Rakotozafy (1996), Ravoavy (1996) and Pfund (in preparation), ranged from 50–5 t ha^{-1} (Table 3).

Table 3 shows that the general nutrient concentration of the vegetation types increased from rainforest to shrub-fallows or mixed fallows, whereas it decreased towards the development of grasslands. This evolution can be explained by the overlapping influence of the leaf proportion and the soil fertility. Leaves have higher nutrient concentrations than their woody parts. In a 5 year-old fallow, leaves had a nutrient concentration which was 2.4–3.9 times higher than its woody components and in a typical species of shrub-fallow (*Psiadia altissima*), leaves were even 6–10 times more concentrated. Therefore, the higher proportion of leaves in shrub-fallows and mixed fallows than in rainforest led to an increased overall nutrient concentration. Under further shifting cultivation, the negative influence of the decreasing soil fertility on phytomass nutrient concentration became more important than the significance of leaves.

3.2.3. Nutrient concentration in topsoils under rainforest and secondary vegetation types

Table 3 shows the relation between the vegetation type and the nutrient concentration in topsoils. Topsoils under rainforest had comparatively low nutrient concentrations. Based on the nutrient inputs from the ashes of the burnt phytomass, concentrations of nutrients increased during the first slash-and-burn cycles.

Table 3
Mean nutrient concentrations in vegetation and topsoils at increasing degradation stages

Nutrient concentration	Rainforest[1]	Shrub fallow	Mixed fallow	Degraded fallow	Grassland
		(*n*=5)	(*n*=4)	(*n*=2)	(*n*=3)
In vegetation					
Phytomass (t ha^{-1})	462	50	15	10	5
C (g kg^{-1})	498	481	472	475	500
N (g kg^{-1})	2.4	5.3	6.3	5.9	4.2
P (g kg^{-1})	0.13	0.50	0.85	0.70	0.80
K (g kg^{-1})	3.2	9.5	8.4	5.3	3.9
Ca (g kg^{-1})	1.9	5.3	5.2	4.3	2.6
Mg (g kg^{-1})	0.5	0.9	2.6	2.3	2.5
In topsoil	(*n*=7)	(*n*=22)	(*n*=15)	(*n*=7)	(*n*=7)
Topsoil thickness (cm)	25	22	20	18	16
Mean bulk densitiy (g cm^{-3})	0.91	0.96	1.05	1.18	1.18
C_{tot} (g kg^{-1})	50±12	51±19	44±12	40±11	37±10
N_{tot} (g kg^{-1})	4.2±1.0	4.0±0.9	3.4±0.6	3.2±0.6	3.0±0.5
P_{av} (mg kg^{-1},Bray)	5.6±3.9	5.2±2.4	8.7±13.6	5.9±2.4	4.6±2.9
K_{ex} (mg kg^{-1})	62±23	109±35	70±31	59±20	78±109
Ca_{ex} (mg kg^{-1})	168±98	514±330	294±256	196±90	122±52
Mg_{ex} (mg kg^{-1})	145±76	186±99	142±94	125±72	89±56

[1]: after Fassbender, 1974.
Abbreviations appearing in subscript: tot- total; av- available; ex- exchangeable; n.m.- not measured.

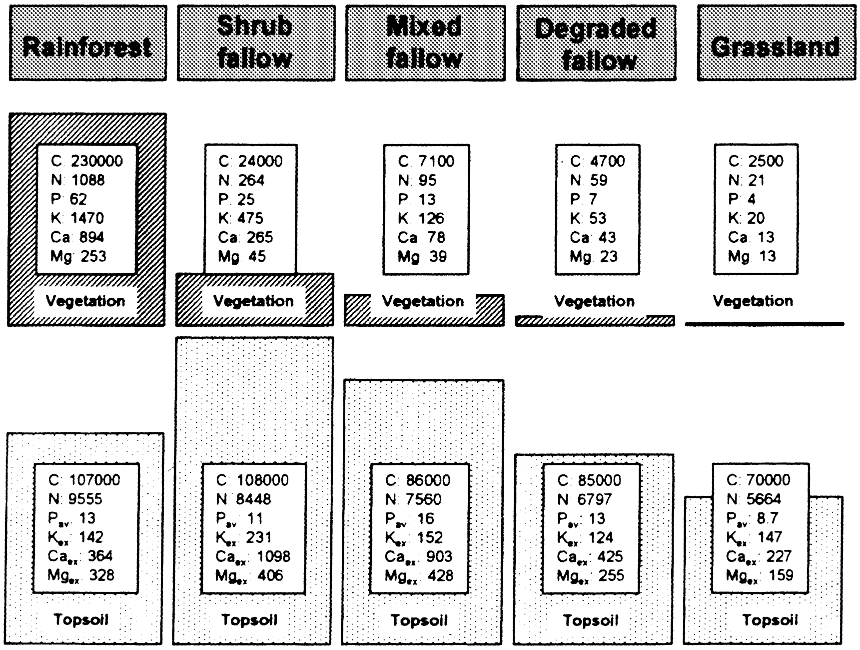

Fig. 3. Mean nutrient stocks (kg/ha) in phytomass and topsoil (0–20 cm) at increasing degradation stages under long-term shifting cultivation. The sizes of the boxes represent the mean proportion of stock of the six analysed nutrients as compared with the first stage (rainforest: 100%).

However, once the stage of shrub-fallow passed, topsoil nutrient concentration decreased continuously and reached its lowest level under grassland. Table 3 clearly shows the peak of the exchangeable cations under shrub-fallow and their subsequent decrease. An exception was recorded for N, which was most concentrated under rainforest.

3.2.4. Dynamics of total nutrient stocks in vegetation and topsoil

Fig. 3 shows that the nutrient stocks in the vegetation types depended mainly on the quantity of phytomass, with the varying nutrient concentrations being less important. At the first degradation stage, a range of approximately 60% (P) to 90% (N) of the phytomass nutrient stock was found to be lost. Under further shifting cultivation, the nutrient stock in the degrading vegetation types decreased continuously, until finally grassland contained merely 1.1% (N) to 6.5% (P) of the initial rainforest stock.

Under long-term shifting cultivation, increasing bulk-density compensates for the decreasing thickness of the topsoil. Therefore, the evolution of the topsoil nutrient stock was very similar to the evolution of the topsoil nutrient concentration. Only the C and N stocks in the topsoil decreased continuously from rainforest to grassland, because of the volatilization losses through repeated burning. However, the stock of exchangeable cations increased temporarily during the first two stages by 89 kg ha^{-1} (K), 734 kg ha^{-1} (Ca) and 100 kg ha^{-1} (Mg), followed by a regular decrease to the stage of grassland. However, nutrient depletion in the topsoil was less dramatic than depletion in phytomass. Under grassland, the topsoil still contained 48–103% of the rainforest topsoil nutrients, whereas the phytomass contained only 1.1–6.5% of the nutrients in rainforest.

The degradation under long-term shifting cultivation was marked by a sharp decrease in the proportion of nutrients accumulated in the vegetation. Under rainforest, 68–91% of the total C, P, K and Ca stocks (vegetation + topsoil) were stored in the phytomass, which is in agreement with the conclusions of Weischet and Caviedes (1993) and Fölster (1986). Jordan (1985) stated, contrary to findings of Sanchez (1979), that under the rainforest the phytomass had a higher Ca stock than contained in the topsoil. In contrast, the topsoil contained 90% of the total N

Table 4
Annual nutrient losses during three successive phases of degradation under shifting cultivation

	From rainforest to shrub fallow	From shrub fallow to degraded fallow	From degraded fallow to grassland
Intensity of shifting cultivation	Intense	Medium	Extensive grazing
Mean fallow duration	2–5 years	4–7 years	Periodically burnt
Duration of transition	5 slash-and burn cycles	10–20 slash-and-burn cycles	50–100 years
Topography	Everywhere	Medium to upper slopes	Upper slopes only
Mean annual nutrient losses			
C (kg ha^{-1} yr^{-1})	12 000	2800	225
N (kg ha^{-1} yr^{-1})	110	123	16
P (kg ha^{-1} yr^{-1})	2.2	1.1	0.1
K (kg ha^{-1} yr^{-1})	52	35	0.1
Ca (kg ha^{-1} yr^{-1})	nr	60	3.0
Mg (kg ha^{-1} yr^{-1})	7.5	12	1.4

(nr: not relevant, gain in topsoil equals loss in vegetation).

and 56% of the Mg stock. These proportions changed rapidly after the first slash-and-burn cycles. The phytomass of a shrub-fallow contained only 10–19% of the total C, Ca and Mg stock, but still 67–70% of the total P and K stocks. After a continuous degradation, the phytomass of the grassland stored merely 0.4% (N) to 32% (P) of the total nutrient stock.

According to Rabevohitra and Randriamboavonjy (1997), nutrient stocks are closely related to hillrice yields. The area of Vohidrazana, characterized by shrub- fallows and mixed fallows, provided an average yield of 1830 kg ha^{-1} of air-dried paddy, against 1516 kg ha^{-1} on the more degraded fields in Salapinga. Analysis for each degradation stage, provided an average yield of 1853 kg ha^{-1} for hillrice plots which were formerly covered by shrub-fallow. Mixed fallow provided 1802 kg ha^{-1}, whereas degraded fallow provided only 1353 kg ha^{-1}. Moreover, it was found that the hillrice yield depended on the toposequential differentiation of soil fertility and increased generally with the age of fallow vegetation.

Fig. 3 indicates the gradual decline of the total nutrient stock as systems degrade. However, nutrient losses especially for total C, P and K, were markedly more important during the first degradation stages than at later ones. 61% of the total C was lost after the first stage. Afterwards, the decreasing rate slowed down to 5–12% from one stage to another. Similarly, total P decreased by 52% during the first stage and 9–12% during each later stage. Even 83% of total K was lost during the evolution from rainforest to mixed fallow. By comparison, total N decreased regularly by 7–18% from one stage to another. However, losses of total Ca and Mg were found to be more important towards the end of the degradation processus. These losses decreased by 18–48% during the evolution of mixed fallow to degraded fallow and then to grassland.

Table 4 shows the annual nutrient losses at different degradation stages, based on the mean duration of fallows and the number of slash-and-burn cycles necessary for the transfer from one stage to another. Although the annual losses of total C decreased in a spectacular manner, N losses started to decrease, only during the final degradation stage. The annual losses of P and K were twice as high during degradation from rainforest to shrub-fallow than from shrub-fallow to degraded fallow, and they became very small during the last degradation stage. The comparatively small loss of Mg and no loss of Ca during the first degradation stage could partly be related to the increasing pH in the topsoil during the first degradation stage (Brand and Rakotondranaly, 1997). The subsequent increase of exchangeable fractions of cations and P could have reduced the figures for P, K, Ca and Mg losses during the first stage.

3.2.5. Nutrient balance

The nutrient balance at site-level for long-term shifting cultivation (Table 5) was calculated for the case of a site at middle slope, that degraded according to Table 4 from the stage of rainforest to the stage of degraded fallow within 125 years of shifting cultivation and 20 slash-and-burn cycles. The inputs and the

Table 5
Nutrient balance at site level (middle-slope) for the long-term degradation from rainforest to degraded fallow under shifting cultivation (approximately 20 slash-and-burn cycles in 125 years)

	IN3	IN4	OUT1	OUT2	OUT4	OUT5	DIFF	TOTAL
C (kg ha^{-1} y^{-1})	nr	nr	119	86	2390	202	821	−1976
N (kg ha^{-1} y^{-1})	7.7	5.0	1.5	2.0	35.2	19.7	16.1	−29.6
P (kg ha^{-1} y^{-1})	2.9	nr	0.1	0.1	nr	0.1	−3.0	−0.4
K (kg ha^{-1} y^{-1})	6.0	nr	3.6	0.7	nr	0.1	−12.2	−11.5
Ca (kg ha^{-1} y^{-1})	6.0	nr	0.9	nr	nr	2.0	−9.4	−6.3
Mg (kg ha^{-1} y^{-1})	6.0	nr	0.6	0.1	nr	1.6	−6.1	−2.4

IN1: Mineral fertilizers (not relevant).
IN2: Manure (not relevant).
IN3: Wet deposition (N, P, K estimates according to Stoorvogel and Smaling, 1990; Ca, Mg according to UNESCO-PNUE, 1979).
IN4: Biological N-fixation (estimates according to Stoorvogel and Smaling, 1990).
IN5: Sedimentation (not relevant).
OUT1: Fuelwood consumption (250 kg ha^{-1} yr^{-1} (Ranjatson, personal communication) with nutrient concentration of a 5-year-old fallow)).
OUT2: Harvest products (removal of 20 harvests of 1.1 t ha^{-1} paddy).
OUT3: Leaching (not measured, included in DIFF).
OUT4: Gaseous losses (continuous denitrification according to Stoorvogel and Smaling, 1990; 20 times volatilization of 98% C and 95% N of 5 year-old fallow stock during burning).
OUT5: Erosion (long-term soil loss of 4.7 t ha^{-1} and nutrient concentration in eroded material according to Brand and Wilfred, 1997).
DIFF: Resulting differences in the balance due to C accumulation from the atmosphere, N, P, K, Ca and Mg deep capture, leaching to deeper soil horizons, wind and water erosion of ashes (a part of the differences may result from the limited number of sites, the important spatial variability and imprecise soil analysis).
TOTAL: Net annual nutrient losses. Difference between the nutrient stocks in the topsoil and the vegetation under rainforest and degraded fallow.
nr: not relevant.

output by fuelwood consumption (OUT1), are the same as in the previously described balance for the hillrice cropping season. Mean annual harvest removal (OUT2) and gaseous losses (OUT4) are 20 times the previously described outputs for one slash-and-burn cycle over 125 years. Brand and Wilfred (1997) measured an average of 4.7 t ha^{-1} yr^{-1} of soil erosion (OUT5) during slash-and-burn and fallow periods. The total annual nutrient losses (TOTAL) represented the differences in total nutrient stocks under rainforest and degraded fallow divided by 125 years.

Table 5 shows that again volatilization through burning caused the highest losses of total C and N. The losses of P and cations were rather the result of fuelwood consumption and erosion than harvest removal. The estimated inputs by wet deposition exceeded the sum of the measured outputs. Under long-term shifting cultivation, the net annual losses of C and P appeared to be 15–20 times lower and those of cations even 30–100 times lower than the losses recorded during the cropping period of slash-and-burn hillrice (Table 2).

3.3. *Catchment-level nutrient balance under long-term shifting cultivation*

3.3.1. *General*

The nutrient balance at the watershed level (Table 6) included the same annual inputs (according to Stoorvogel and Smaling, 1990) as the preceding balances. Compared with the previously described annual output through fuelwood consumption (OUT1) and according to Fig. 2, only 98% of the C stock and 95% of the N stock were supposed to be lost from the watershed (volatilization), and the other nutrients remained in the ashes within the watershed. Also, the consumption of harvested products was expected to occur within the watersheds. The percentage of nutrients, lost by human consumption (OUT2) of the harvest, was calculated according to figures reported by Falisse and Lambert (1994). The annual gaseous losses (OUT4) for the watersheds depended on the annual slash-and-burn surface, which increased from 3.2% in Vohidrazana (initial stage) to 12.6% in the watershed of Salapinga (degraded stage). There-

Table 6
Nutrient balance at watershed-level for the long-term degradation from a forested watershed to a degraded watershed under shifting cultivation (200 years)

	IN3	IN4	OUT1	OUT2	OUT4	OUT5	DIFF	TOTAL
C (kg ha^{-1} y^{-1})	nr	nr	117	30	1494	91.8	848.8	−884
N (kg ha^{-1} y^{-1})	7.7	5.0	1.4	0.7	24.1	26.7	28.3	−11.9
P (kg ha^{-1} y^{-1})	2.9	nr	nr	nr	nr	9.4	6.3	−0.2
K (kg ha^{-1} y^{-1})	6.0	nr	nr	0.1	nr	21.1	10.3	−4.9
Ca (kg ha^{-1} y^{-1})	6.0	nr	nr	nr	nr	12.0	4.1	−1.9
Mg (kg ha^{-1} y^{-1})	6.0	nr	nr	nr	nr	13.3	6.5	−0.8

IN1: Mineral fertilizers (not relevant).
IN2: Manure (not relevant).
IN3: Wet deposition (N, P, K estimates according to Stoorvogel and Smaling, 1990; Ca, Mg according to UNESCO-PNUE, 1979).
IN4: Biological N-fixation (estimates according to Stoorvogel and Smaling, 1990).
IN5: Sedimentation (not relevant).
OUT1: Fuelwood consumption (volatilization of 98% C and 95% N in the fuelwood (250 kg ha^{-1} yr^{-1}, Ranjatson, personal communication) with nutrient concentration of a 5-year-old fallow).
OUT2: Harvest products (loss of 50–60% C and N and 20–40% P and K (Falisse and Lambert, 1994) through consumption of the annual harvest of 1.1 t ha^{-1} paddy on 10% of the watershed surface).
OUT3: Leaching (not measured, included in DIFF).
OUT4: Gaseous losses (continuous denitrification according to Stoorvogel and Smaling, 1990; annual volatilization of 98%C and 95%N of 5 year-old fallow stock on the burnt 10% of the watershed surface).
OUT5: Erosion (annual loss of nutrients in sediment charge and soluble nutrients in river discharge according to Brand and Wilfred, 1997).
DIFF: Resulting differences in the balance due to C accumulation from the atmosphere, N, P, K, Ca and Mg deep capture, leaching to deeper soil horizons (A part of the differences may result from the limited number of sites, the important spatial variability and imprecise soil analysis).
TOTAL: Net annual nutrient losses at watershed-level. (Difference between the nutrient stocks in the topsoil and the vegetation of a forested watershed and a degraded watershed).
nr not relevant.

fore, the long-term annual slash-and-burn surface was estimated to be 10% of the watershed surface. As for fuelwood consumption, 98% of phytomass-C and 95% of phytomass-N were supposed to be lost from the burning of these surfaces. Measured annual export of nutrients through river discharge (OUT5), resulting from soil erosion and leaching, was 2.5–4 times higher in the degraded watershed than in the mainly forested watershed. This increased nutrient discharge, seems to be in contradiction with the preceding results (Table 4), which stated that the annual nutrient losses at site level were highest during the initial phase of shifting cultivation. This phenomenon could be explained by the fact that 85% of the watershed surface of Vohidrazana was still under rainforest with an almost closed nutrient cycle (Jordan, 1985; Juo and Manu, 1996). Supposing that the exported nutrients in Vohidrazana originated mainly from the 15% of surface under shifting cultivation, the export per hectare under shifting cultivation appeared to be 1.5–2.5 times higher than in Salapinga. However, the average nutrient charge of the two watersheds in 1994–1995 (Brand and Wilfred, 1997) was taken as the mean annual export of nutrients through river discharge (OUT5) under long-termed shifting cultivation.

The balance is based on a comparison between the overall nutrient stocks of the forested watershed of Vohidrazana, which stands for the initial stage of shifting cultivation, and the degraded watershed of Salapinga, where shifting cultivation has been practised for approximately 200 years (Brand and Zurbuchen, 1997). Based on the reclassified vegetation maps of the two watersheds (Vololonirainy, 1995), the total nutrient stocks for the vegetation types (Table 3) were multiplied by their respective surfaces. For the topsoils of hillrice surfaces, the average from topsoil nutrient contents under shrub-fallow, mixed and degraded fallow were applied, and the phytomass was discounted. This method provided the total nutrient stocks for both watersheds. The long-term average of net annual losses (TOTAL in Table 6) for watersheds under shifting cultivation was calculated by dividing the difference between the calculated stocks by the approximately 200 years of agriculture.

3.3.2. Nutrient balance

The long-term balance for watersheds (Table 6) indicates that the most important losses of C were from slash-and-burn and to a lesser extent from fuelwood consumption and erosion. Similar amounts of N were lost to the watershed through burning and river discharges, whereas P and cations were almost exclusively lost through river discharge. At watershed scale, wet deposition became an important supply of N, P and cations.

The resulting positive difference (DIFF in Table 6) reflects the important amounts of accumulated C and deep captured N, P and cations. According to Stoorvogel and Smaling (1990), these gains may partly be the result of downward extension of the root zone and the topsoil during long-term shifting cultivation. As total topsoil P and cations were not measured, a part of the resulting gains might be attributed to a gradual transfer from the fixed fractions to the exchangeable fractions, which is triggered by the continuous nutrient depletion.

Comparing the different nutrients, three different figures could be distiguished at watershed-level (Table 6). C was mainly lost through burning, from which half was compensated by phytomass accumulation. N was lost at equal parts through phytomass burning and river discharge. The annual N losses, exceeded slightly the annual gains from deep capture, wet deposition and biological N-fixation. P and cations were exclusively lost through river discharge, but here also, inputs through deep capture and wet deposition almost compensated for the annual outputs.

At watershed-level, the inflows and outflow of nutrients exceeded by far the low net losses (Table 6). The annual net losses (TOTAL) of the measured nutrients were below 0.5%, in comparison with the total nutrient stocks in the system. The annual outputs and inputs of P rose to 12.5% of the total P stock in the system, which was because of a high soluble P discharge in the rivers and low content in the system.

4. Conclusions

There is an urgent need for improvement of current unsustainable slash-and-burn agriculture, with regard to nutrient status and biodiversity. According to this study, improved fallow species, agroforestry systems and reduction of excessive nutrient losses during the cropping phase through improved burning techniques and synchronized plant requirements and nutrient supplies should have higher priority than soil-conservation techniques. Yet, reducing the high nutrient losses during the initial stage of shifting cultivation is a real challenge, as farmers are reluctant to change their traditional techniques when yields are still satisfactory. As sustainable improvements can only be achieved through discussion and with the participation of all concerned farmers, higher priority should be attributed to participatory research. However, providing more appropriate information on the long-term consequences of shifting cultivation to farmers, decision makers and researchers might be another step towards improved agricultural systems in slash-and-burn areas.

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