Degrading uplands in the rainforest region of Madagascar: Fallow biomass, nutrient stocks, and soil nutrient availability

Erika Styger · Erick C. M. Fernandes · Harivelo M. Rakotondramasy · Eric Rajaobelinirina

Abstract Soil fertility restoration depends on natural fallows in the slash-and-burn system of eastern Madagascar. In the Beforona-Vohidrazana study zone, none of the fallow species are able to withstand the slashing, burning and cropping frequencies of 3–5 years. Eventually soils are abandoned for agriculture. Along the degradation sequence, this study quantifies fallow biomass, nutrient stocks and soil nutrient availability of four dominant fallow species *Trema orientalis, Psiadia altissima, Rubus moluccanus,* and *Imperata cylindrica*. At 3 years, the shrubs *Psiadia* and *Rubus* were more productive (11–14.4 t/ha aboveground biomass or AGB) than the tree species *Trema* (8.5 t/ha). Only after 5 years did tree productivity (24.7 t/ha) exceed that of shrubs (17–20 t/ha). *Imperata*'s biomass stagnated at 5.5 t/ha after 3 years. A sharp decline in fallow productivity was observed with advancing fallow cycles after deforestation. While *Psiadia* produced highest AGB in the second fallow cycle (C2) being 100%, C1 achieved 89% of that, C3 74%, and C4 only 29%. With the ability to propagate vegetatively and to accumulate important amounts of nutrients in roots, *Rubus* and *Imperata*, both exotic and invasive species, showed improved adaptation mechanisms towards frequent disturbances compared to the two indigenous species *Trema* and *Psiadia*. Available soil nutrients P, K, Mg were highest under forest and declined rapidly with increasing fallow cycles. Ca and pH rose momentarily in the first fallow cycle before declining with advanced soil use. Al concentrations increased steadily with time. As lengthened fallow periods are not practical, there is a need to intensify upland systems based on improved nutrient cycling, targeted inputs, fire-less land management, and land use diversification. Allowing regrading tree and bush fallows to accumulate biomass (above- and below-ground carbon) will significantly improve Madagascar's greenhouse gas mitigation contribution.

Keywords *Tavy* · Succession · Carbon sequestration · Slash-and-burn · Shifting cultivation · Biodiversity · Soil carbon · Geospatial data

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Introduction

The fallow phase in a slash-and-burn cultivation cycle is responsible for soil fertility restoration in which over a period of several years nutrients are taken up from the subsoil, surface soil and the atmosphere and stored in tissues of growing vegetation. The burning of the forest or fallow biomass results in the release of nutrients that can be utilized by crops planted after the burn (Nye and Greenland 1960; Sanchez 1976). The successful regeneration of soil productivity via fallows depends on the extent of past soil degradation, the characteristics of the fallow species and successional vegetation community, and the length of the fallow period (Uhl 1987; Kleinman et al. 1995). This translates into the rate and magnitude of nutrient accumulation in plant biomass and surface soil pools. Biomass production in a fallow is a direct index of ecosystem primary productivity and nutrient cycling (Whittaker and Marks 1975).

The traditional slash-and-burn agricultural system (*tavy*) is the dominant land use in eastern Madagascar, where forests or fallows are cut, burned and upland rice is usually cultivated for 1 year. Soil restoration depends solely on the spontaneously regenerating natural fallow vegetation. In the Beforona-Vohidraz-ana study zone, a shortening of fallow periods took place from previously 8–15 years in the 1970s to

3–5 years currently. The *tavy* system is collapsing and land degradation is accelerating quickly across the landscape. The decline in agricultural productivity becomes a driving factor for young people to migrate to the forest boundary and to continue cutting down rainforest in search for new land (Styger et al. 2007). The breakdown of agricultural systems, which are based on natural fallows for soil restoration, has been observed across the globe. With a shortening of the fallow cycles, tree species are unable to regenerate and are displaced by pioneer shrubs and grasses. The loss of woody regrowth and the dominance of grass fallows are often associated with a permanent lowering of soil fertility. The land often becomes unsuitable for cropping, and is finally abandoned for agriculture (Nye and Greenland 1960; Ruthenberg 1980; Cairns 2004; Styger and Fernandes 2006).

Under the fallow periods of 3–5 years, a distinct fallow species change can be observed with each additional fallow cycle in the Beforona-Vohidrazana area (Fig. 1). The first fallow cycle after deforestation is dominated by *Trema orientalis* and *Harungana madagascariensis*. Theses trees are replaced in the second cycle by the endemic shrub *Psiadia altissima*. *Psiadia* remains the dominant shrub in subsequent cycles, unless it is out-competed by the exotic invasive species *Rubus moluccanus* or *Lantana camara*. Beyond the fifth cycle after deforestation, ferns and

Fig. 1 Fallow species succession as a function of cropping/fallow cycle and time since deforestation
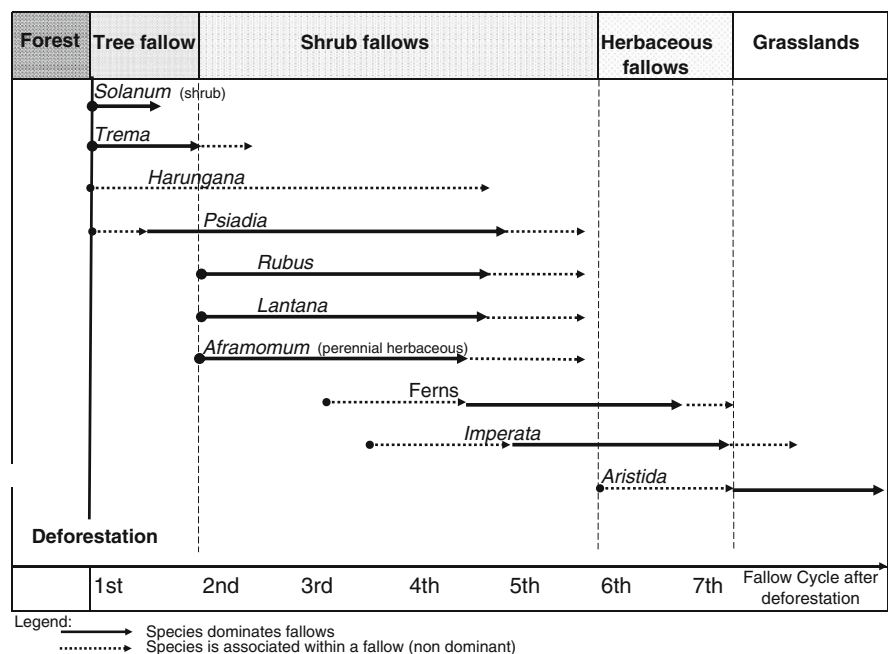
Imperata cylindrica are replacing the woody vegetation. Eventually, after continued slashing and/or burning, they are replaced by the grasses *Aristida* sp. representing the last stage in the succession from forest to grass. Farmers abandon the land for agriculture and use it only occasionally for grazing. The transition from mature rainforest to abandoned grasslands takes under the current fallow periods only between 20 and 40 years (Styger et al. 2007), which is 5–12 times faster then stated by Chauvet (1972) and by Brand and Pfund (1998) for the study zone.

Although the *tavy* system has been recognized for over 150 years to be a major threat to the natural resources in Madagascar (Humbert 1927; Kiener 1963; Oxby and Boerboom 1985; Gade 1996; Marcus 2001) comparatively little research has been done to study associated land cover and land degradation dynamics. Fallow studies in eastern Madagascar concentrated on botanical description of vegetation groups (Humbert 1927; Lowry et al. 1997), or related succession to soil properties (Dandoy 1973; Razafintsalama 1996; Pfund 2000). Brand and Pfund (1998) measured biomass and nutrient stock accumulation in fallows based on broad vegetation categories and fallow age. The direct link to current land use practices was established by Randriamalala et al. (2007) who studied the composition of fallow vegetation in relation to cumulated length of cropping periods, soil preparation, and fallow age in the highland zone of the Ranomafana-Andringitra forest corridor. For the study zone, Styger et al. (2007) investigated the change in fallow species composition with regard to frequency and length of fallow cycles, and agricultural practices. This study represents a follow up of the identified vegetation change along the degradation sequence presented in Styger et al. (2007). The objective was to characterize four main fallow species along a land degradation gradient by quantifying their biomass, nutrient stocks and soil nutrient availability, by taking into account fallow cycle numbers following deforestation, and fallow age.

Methodology

Site characteristics

The study was carried out near the Mantadia-Zahamena rainforest corridor, one of the largest remaining contiguous forests located in the central part of the eastern escarpment of Madagascar. The rainforests are classified as evergreen humid forests at low (0–800 m) and mid altitude (800–1,800 m) (Humbert 1955; Faramalala 1995; Du Puy and Moat 1996). The study zone represents a typical transect of the eastern forest and escarpment. The altitude ranges between 750 and 1,200 m (a.s.l.) in the west of the study zone that is still covered by forest. Further east, the altitude of the Betsimisarka escarpment declines from 750 to 350 m (a.s.l.) with increasing distance from the forest. The drop in altitude goes in parallel with the change from tree to shrub to herbaceous fallow vegetation. This change is linked to the deforestation history of the area, which started in the east at the coast, and gradually moved westwards and uphill (Brand 1997; Brand and Zurbuchen 1997).

The zone is characterized by a tropical humid climate with an annual rainfall between 2,000 and 3,500 mm and annual average temperatures ranging from 17 to 21.5°C (Brand 1997). Sampling of fallow plots occurred in locations representative of the dominant fallow vegetation within the study zone. The three main sites were Beforona, at 550 m (a.s.l.), 18°58′12″S, 048°35′41″E, Ambavaniasy at 695–850 m, 18°56′49″S, 048°30′38″E, and Berano, 930 m, 18°50′55″S, 048°19′55″E. The geology of the eastern region is characterized by metamorphic and igneous rock, including crystalline rocks such as granites, migmatites and schists (Besairie and Collignon 1960; Du Puy and Moat 1996). The soils in the study zone are Inceptisols and Ultisols with acid surface soils (pH of 3.5–5.0). Aluminum saturation is between 60 and 90% and nutrient contents, especially phosphorus, in surface and subsoils are extremely low (Johnson 1992; Brand and Rakotondranaly 1997).

Fallow species selection

In the Vohidrazana/Beforona area, fallows are often dominated by a single species of tree, shrub or herb, or appear in mixtures of a few species. The most important fallow species of the region have been described in Styger et al. (2007). For this study, the four main fallow species were selected that are found along the land degradation sequence: *Trema orientalis* Blume (Ulmaceae), *Psiadia altissima* (DC.) Drake (Asteraceae), *Rubus moluccanus* L. (Rosaceae), and *Imperata cylindrica* (L.) Raeusch. (Poaceae)

(Table 1). Among them, *Psiadia* is the only species occurring across all woody species cycles (Fig. 1). Thus, the first four fallow cycles of this species were integrated into the study allowing for the comparison between cycles without the change of species.

Fallow plot selection, transects and measurements

Four each of the four species, five fallow fields were selected (Table 2), representing replicates, to establish allometric regression models for biomass estimation and to take plant and soil samples. Field selection criteria included uniform growth of the fallow vegetation, a nearly mono-specific stand of the studied species, and a fallow vegetation with a closed canopy. Within a fallow field, which was 1–2 ha in extent, a transect of 2 m × 20 m was delimited on the mid-slope parallel to the slope, avoiding crests and hill bottoms. Soil sampling was done in each of the transects, as described below.

For *Trema* and *Psiadia*, ten trees were selected in each transect for biomass harvest, covering the range of diameter classes of that stand. In addition, seven *Trema* trees and four *Psiadia* trees were harvested outside of the studied transects, but within the same fallow, representing larger diameter trees that could not be found within the transects. As *Rubus* forms a thick, spiny, and impenetrable stand, five plots per field of 3 m × 3 m were positioned along a 20 m transect line, where soil samples were taken. For *Imperata*, the layout was the same as for *Rubus*, but with a plot size of 1 m × 1 m. For these two species, total plots were harvested and individual plant measurements subsequently taken.

Thus, biomass components were weighed for 57 *Trema* trees, 54 *Psiadia* trees and for 25 plots for *Rubus* and *Imperata*. Measured biomass components included: leaves, branches, stem, wood (sum of stem and branches), primary roots, secondary roots (all coarse roots that were not primary roots and that were >2 mm in diameter), fine roots (<2 mm), and the root bulb for *Rubus*, which was a species-specific feature. The biomass data obtained in the transects were used to establish allometric regression models to predict above and below ground biomass components (dependent variable *y*) through a predictor variable, which was diameter for *Trema* and *Psiadia*, root bulb weight for *Rubus* and leaf biomass for *Imperata*.

For the study of biomass in relation to fallow age and fallow cycle for *Psiadia*, fallows from 1 to 10 years in age were selected for *Trema*, and from 1 to 8 years in age for *Psiadia* for each of the first four fallow cycles after deforestation. Age and cycles were identified based on farmers' information. Three transects of 2 m × 20 m were laid out in the mid-slope and parallel to the slope, and diameter measurements were taken of all individuals within the transects. Thus for *Trema*, we measured a total of 30 transects (3 transects per year × 10 years), and for *Psiadia* 96 transects (3 transects per year × 8 years × 4 cycles). The newly established allometric equations, reported in Styger (2004), were applied to the individual tree diameters. The individually calculated biomass was then summed per area sampled and then converted to biomass in kg/ha for each of the biomass components. As *Rubus* and *Imperata* did not show a relationship between biomass and age for the 25 plots harvested, no further harvesting of various aged plots was undertaken. The data obtained from the 25 harvested plots were converted into kg/ha.

Plant and soil sampling and nutrient analysis

For each harvested biomass component, a composite sample of five to eight sub-samples was taken per transect. The five transects represented five repetitions. Wood and root samples were approximately x-300 g and leaf samples y-100 g fresh weight. They were measured in the field with precision balances of 1,000 g (10-gram precision) and 100 g (1-gram

Table 1 Characteristics of four studied fallow species from the Beforona-Vohidrazana area

Fallow type	Species	Family	Origin	Fallow cycle after deforestation
Tree fallow	*Trema orientalis* (L.) Blume	Ulmaceae	Pantropical	First
Shrub fallow	*Psiadia altissima* (DC.) Drake	Asteraceae	Endemic	First to fourth
	Rubus moluccanus L.	Rosaceae	Exotic and invasive	Third to fifth
Herbaceous fallow	*Imperata cylindrica* (L.) Raeusch	Poaceae	Pantropical	Fifth to sixth

Table 2 Characteristics of sampled transects

Transect number	1	2	3	4	5
Rainforest					
Site	Berano	Marolafa-Beforona	Ambavaniasy	Ampahitra	Ankeniheny
GPS S:	18°50′55″	18°57′51,03″	18°57′03″	19°04′29″	–
GPS E:	048°19′50″	48°35′09,26″	048°29′46″	048°14′01″	–
Exposition	E	N	W	S	NW
Slope (%)	35	40	50	50	30
Trema orientalis					
Site	Berano	Berano	Ambavaniasy	Beforona	Beforona
Location	Berano valley	Berano valley	Analambalo	Ambatomalama	Beforona village
GPS S	18°50′55″	18°51′05″	18°57′03″	18°58′12″	18°57′14″
GPS E	048°19′50″	048°19′38″	048°29′46″	048°35′00″	048°35′14″
Exposition	W	W-NW	EEN	SSE	SSE
Slope (%)	15	13	40	25	25
Psiadia altissima					
Sites	Ambavaniasy	Ambavaniasy	Ambavaniasy	Ambavaniasy	Ambavaniasy
Location	Ambatosenegal	Ambatosenegal	Ambavaniasy	Ambatosenegal	Andranonampango
GPS S	18°57′19″	18°57′14″	18°56′49″	18°57′03″	18°56′28″
GPS E	048°29′41″	048°29′42″	048°30′38″	048°29′46″	048°30′57″
Exposition	E	NE	NE	SSE	ENE
Slope (%)	15–20	10	45	35	35–45
Rubus moluccanus					
Site	Beforona	Beforona	Beforona	Beforona	Beforona
Location	CDIA-Marolafa	Ambinanisahavolo	Amalomananika	Ambatomalama	Ambatomalama
GPS S	18°57′52″	18°58′11,63″	18°56′48,52″	18°58′26,23″	18°58′14,42″
GPS E	048°35′14″	48°35′40,71″	48°35′15,95″	48°35′50,24″	48°35′39,68″
Exposition	S	N	SE	E	S
Slope (%)	20–30	20–30	30–40	45	10–15
Imperata cylindrica					
Sites	Beforona	Beforona	Beforona	Beforona	Beforona
Location	CDIA-Marolafa	CDIA-Marolafa	Ambinanishavolo	Fotsihalanana	Amalomanarika
GPS S	18°57′34,33″	18°57′04,05″	18°56′52,24″	18°56′46,42″	18°56′46,47″
GPS E	48°35′16,55″	48°35′22,03″	48°35′21,33″	48°35′07,16″	48°35′16,31″
Exposition	W	E	E	NE	E
Slope (%)	45	55	65	25–30	30–35

precision). The samples were air-dried in paper bags until transport to the main lab for oven drying. The samples were dried at 50°C until no further weight loss was observed and dry weight was measured. Samples were exported to the CALS Laboratories, Cornell University, Ithaca, NY, USA where macro- and micronutrients in plants were analyzed through acid digestion with HNO_3, and ICP spectrometry. Nitrogen and carbon were identified through stable isotope analysis and mass spectrometry.

Soil sampling for nutrient analysis was done in each transect. Ten soil samples were taken along the middle line of the 20 m long transect with a soil auger to a depth of 20 cm. The 10 auger cores were combined in a plastic bucket, rocks and organic debris removed, and the remainder well mixed. A sample of ca 500 g was removed and air-dried in a paper bag in open air for at least 2–3 weeks. Dry soil was exported to CALS Laboratories, Cornell University, Ithaca, NY. Soil nutrients were analyzed with

Morgan's extraction and ICP spectrometry. The analysis of difference between the four fallows for soil and plant nutrients was done with an ANOVA analysis using the adjusted Tukey-Kramer as a test of significance at a level of $P < 0.1$ with the computer program SAS, release 8.02 (SAS 2001).

Results

Biomass production of four fallow species

Growth and biomass accumulation differed for each of the species within the time span from 1 to 10 years of age. Whereas *Trema* had an exponential growth curve, *Psiadia*'s growth was linear. On the other hand, *Rubus* and *Imperata* did not show a relationship between age and total biomass after canopy closure occurring at the ages of 3–4 years.

Comparison of biomass among the four species is shown in Fig. 2. This analysis focuses on the fallow periods of 3–5 years, which are most prevalent in the region. They are compared to 8-year fallow periods, which are clearly preferred by farmers, but due to increased pressure on land have become very rare in the study zone.

Trema's initial growth was slow due to its exponential growth curve. At the age of 3 years, above-ground biomass (AGB) attained only 8% (or 8.5 t/ha) of its 10-year biomass (107 t/ha). At 5 years, AGB reached 25% of the 10-year value. In relation to above ground biomass, total root biomass declined with age. Expressed as root/shoot ratio (root mass/shoot mass), the value dropped from 0.37 to 0.16 from 1 to 10 years. Our data show that *Psiadia* accumulates biomass at the same rate over the fallow periods studied. At the age of 3 years, AGB of first cycle *Psiadia* reaches 14.7 t/ha, which is about 6 t/ha higher then for *Trema*. At the age of 5 years, however, *Psiadia* is overtaken by *Trema*, and at 8 years it attains less then half of *Trema*'s biomass (31.6 and 67.4 t/ha, respectively). The root/shoot ratio increased slightly over the years from 0.15 to 0.19. Contrary to the other studied woody species, biomass accumulation of *Rubus moluccanus* showed no relationship between biomass yields and age beyond 4 years of age. Once the canopy closure occurs around the age of 3 years, there is no significant increase in plant height and biomass with fallow age. The AGB from 4 to

10 year-old *Rubus* fallows was on average 15.9 t/ha. *Rubus* had a high root/shoot ratio of 0.53. 34% of the root biomass was attributed to the root bulb, a species-specific feature. Similarly to *Rubus*, *Imperata* showed no biomass increase with age beyond 3 years of age. Average ABG was 5.54 t/ha and like *Rubus*, the root/shoot ratio was high being 0.55.

Comparing biomass accumulation among the four species, at the age of 3 years, *Psiadia* in C1, C2 and *Rubus* were the most productive species with AGB between 11–14.4 t/ha. *Trema* produced only two-thirds and *Imperata* and *Psiadia* C4 only a quarter of that biomass. At 5 years of age, the *Trema* fallow produced 24.7 t/ha of AGB. By comparison, AGB of *Psiadia* C1, C2 and *Rubus* reached only between 70–80%, *Psiadia* C3 about 50%, and *Psiadia* C4 and *Imperata* 24% of the *Trema* AGB. After 8 years of growth, the three best shrub fallows accumulated less then half of *Trema*'s biomass, for *Psiadia* C3 it was 35%, and for *Psiadia* C4 and *Imperata* only 15 and 8%, respectively. Whereas at young fallow age, shrubs were most productive, with advancing fallow age the gradient of fallow productivity from tree to shrub to herbaceous fallow became more pronounced.

Psiadia's biomass productivity with increasing fallow cycles

The comparison of *Psiadia*'s biomass production from the first to the fourth cycle (C1–C4) after deforestation permits an examination of fallow productivity associated with advancing cycles after deforestation, independent of species change. Yearly biomass increase for four cycles is presented in Fig. 3. Above ground biomass accumulation in the *Psiadia* fallow was greatest in the second and first cycle with 4.4 and 3.9 t/ha/year, respectively, then declined to 3.3 t/ha for C3 and 1.3 t/ha for C4. Comparing the AGB increase with C2 being 100%, C1 produced 89%, C3 74%, and C4 only 29% which shows a sharp productivity decline especially after the third fallow cycle after deforestation.

Plant nutrient concentrations

The nutrient concentrations of leaves, wood and roots for the four fallows are presented in Fig. 4. *Trema*'s and *Psiadia*'s leaf concentrations for N, P, K were significantly higher compared to *Rubus* and *Imperata*.

Fig. 2 Biomass production (kg/ha) for four fallow species, according to cycles after deforestation at ages of (a) 3 years, (b) 5 years and (c) 8 years
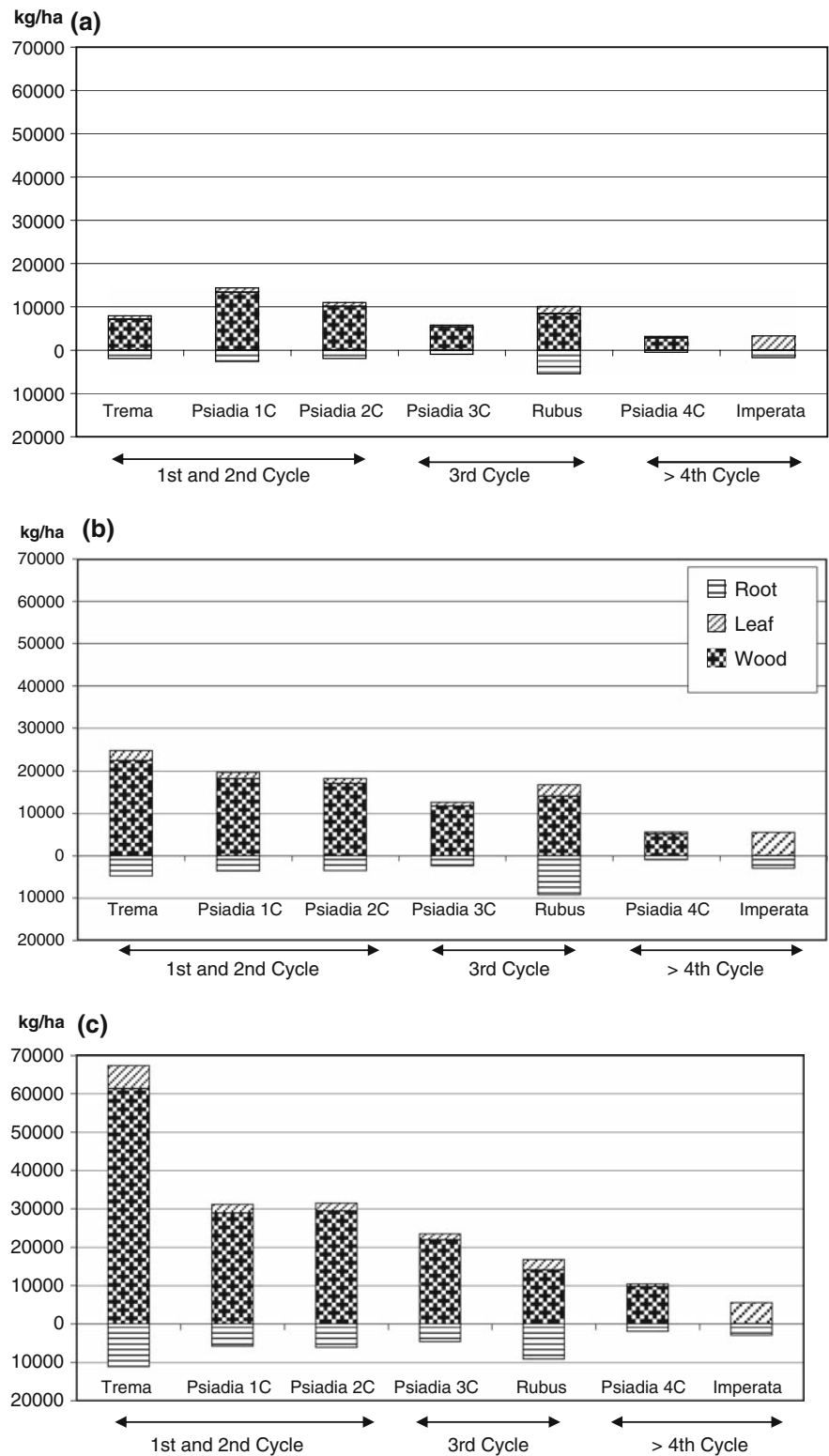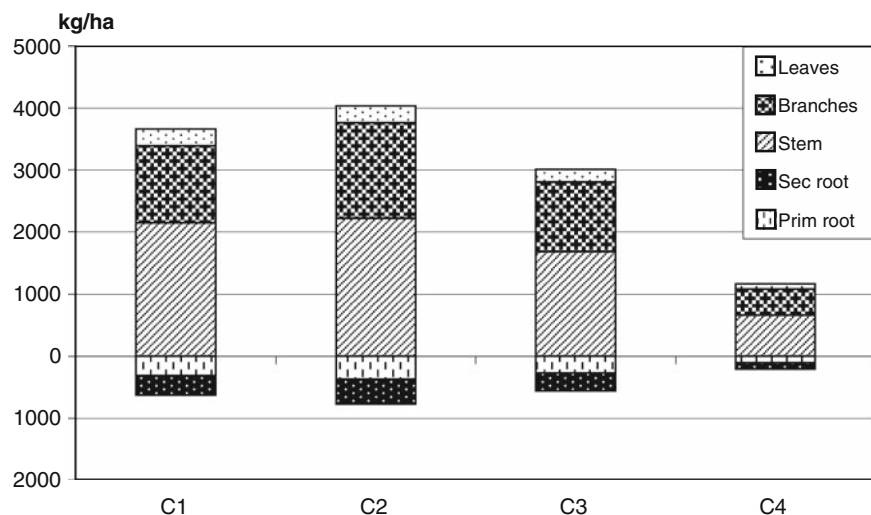
Fig. 3 *Psiadia altissima* annual biomass accumulation (kg/ha) for four cycles after deforestation (C1–C4)

Trema's leaf N (2.63%), for instance, was two to five times that of *Rubus* and *Imperata*, respectively. *Psiadia* was an excellent K and S accumulator (35,290 and 2,530 mg/kg, respectively), but had low Mg levels (1,876 mg/kg) in its leaves. *Rubus*, on the other hand, accumulated Mg well in its leaves (7,350 mg/kg), but showed relatively low concentrations of K (6,230 mg/kg). Compared with the other species, *Rubus* had the highest N, Mg, and Ca concentrations in roots. Its wood and root P values (910 and 795 mg/kg, respectively) were two to four times higher than in *Trema* and *Psiadia*. Among the four species, *Imperata* had the lowest leaf macronutrient concentrations. However, its root K, P, and S levels were higher then in *Trema* and *Psiadia*. *Imperata* accumulated Al, especially in its roots (1,846 mg/kg). Conversely, Ca concentration was extremely low in leaves (724 mg/kg or 20 times lower than in *Trema* leaves), and in roots (254 mg/kg or 27 times lower than in *Rubus* roots). In summary, the early succession species *Trema* and *Psiadia* had relatively higher nutrient concentrations in their leaves compared to root and wood, whereas *Rubus* and *Imperata* showed higher nutrient concentrations in roots and wood (for *Rubus*) compared to leaves.

Fallow nutrient and carbon stocks

Calculated total nutrient and carbon stocks (above and belowground) for all species at the fallow age of 3, 5 and 8 years are presented in Table 3. At 3 years, with the exception of K, the exotic species *Rubus* accumulates more nutrient stocks then the native

species *Psiadia* and *Trema* despite its inferior biomass. *Rubus* nutrient stocks are still superior to *Psiadia*'s after 5 years of growth. At that same age, they are lower than *Trema*'s nutrient stocks for N and K, equal for Mg and Ca, but still higher for P and S. It is only at 8 years when *Psiadia* (first and second cycle) surpasses *Rubus* in most macronutrient stocks except for P and Mg. *Imperata* accumulates more nutrients then fourth cycle *Psiadia* up to the age of 5 years. In conclusion, improved nutrient stocks of *Rubus* and *Imperata* relative to *Trema* and *Psiadia* in the initial fallow years are influenced by considerable nutrient accumulation in their roots.

Available soil nutrients and pH

Available soil nutrients concentrations to a depth of 0–20 cm, and soil pH are shown in Fig. 5. The highest soil nutrient concentrations of P and K were found under forest, followed by *Trema* and then declined for P, to almost non detectable levels under *Psiadia*, *Rubus* and *Imperata*, and for K to about half of the forest value. Similarly, Mg levels declined with advanced soil degradation. Ca increased with cultivation from the original forest value from 256 mg/kg to 414 mg/kg under *Trema*, but then dropped to 101 mg/kg under the *Imperata* fallow. Soil acidity was significantly higher under forest with pH 4.35 compared to the four fallow vegetations (pH 5.15–5.48). Lowest soil acidity was observed in the first fallow after deforestation under *Trema* with pH 5.48 and thereafter turned steadily more acidic to pH 5.15 in *Imperata*. Aluminum
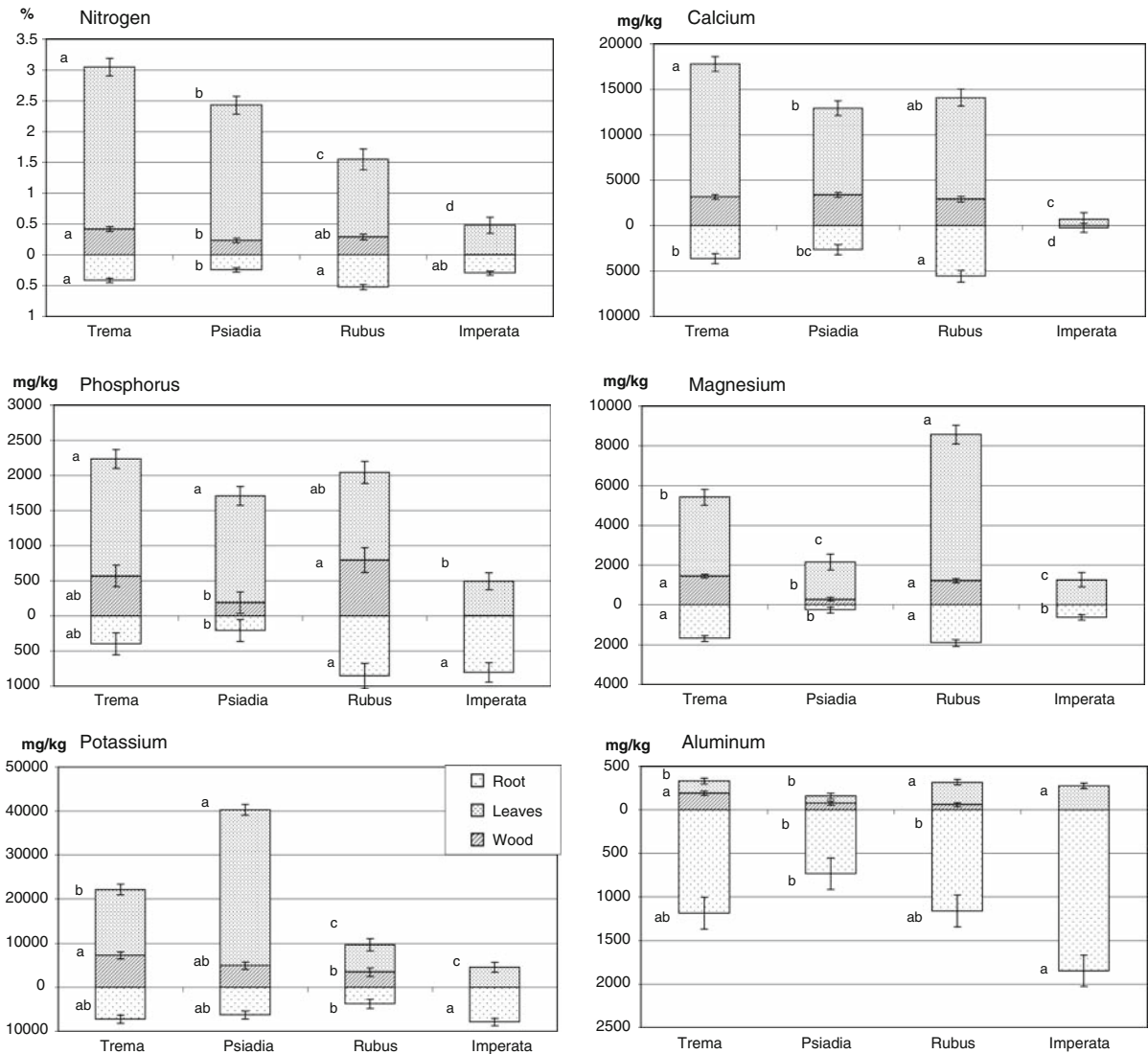
Fig. 4 Nutrient concentration of biomass components (leaves, wood and roots) for four species in % for nitrogen, and in mg/kg for phosphorus, potassium, calcium, magnesium and

aluminum ($n = 5$ transects; adjusted Tuckey-Kramer test $P < 0.05$; 2 SE; Means that are followed by the same letter are not significantly different at $P < 0.05$)

concentrations increased steadily with increased soil use and were 224 mg/kg in *Imperata* compared to the initial forest values of 104 mg/kg.

Discussion

Biomass production of four fallow species

Identifying initial growth behavior of fallow species is essential when evaluating the efficiency of short-

term fallows. Reports on fallow growth curves vary from exponential (Nakano and Syahbuddin 1989; Feldpausch et al. 2004); linear (van Reuler and Janssen 1989; Kotto-Same et al. 1997; Ohtsuka 1999; Szott et al. 1999; Hartemink 2001), to more rarely logarithmic (Nye and Greenland 1960). Initial growth curves were exponential for *Trema*, linear of *Psiadia* and did not exhibit a relationship between age and biomass for *Rubus* and *Imperata* after the age of 3–4 years. The assumption that tree fallows produce superior biomass than shrub fallows and

Table 3 Nutrient and carbon stocks (kg/ha) for total biomass (above and below ground) for four fallow species and four cycles for *Psiadia*, at 3, 5, and 8 years

	Yields (kg/ha)	C (kg/ha)	N (kg/ha)	P (kg/ha)	K (kg/ha)	Mg (kg/ha)	Ca (kg/ha)	S (kg/ha)
3 Years								
Trema	9,980	4,934	59	6.2	78	16.9	41.3	3.6
Psiadia C1	14,004	7,203	51	3.9	101	5.5	51.9	7.6
Psiadia C2	10,952	5,631	40	3.0	78	4.2	40.4	5.9
Psiadia C3	7,128	3,667	26	2.0	51	2.8	26.4	3.9
Rubus	14,513	6,863	68	12.6	57	29.4	72.4	10.1
Psiadia C4	3,703	1,907	14	1.0	27	1.5	13.9	2.1
Imperata	5,139	2,380	21	3.0	30	5.4	2.8	4.9
5 Years								
Trema	29,717	14,725	173	18.5	233	49.9	121.9	10.8
Psiadia C1	22,784	11,714	82	6.2	163	8.8	84.1	12.3
Psiadia C2	20,796	10,681	73	5.6	146	7.9	76.0	11.1
Psiadia C3	14,452	7,425	51	3.9	102	5.5	53.0	7.7
Rubus	24,188	11,438	113	21.0	94	9.0	120.7	16.8
Psiadia C4	6,522	3,354	24	1.8	47	2.5	24.1	3.6
Imperata	8,565	3,966	35	5.0	49	9.0	4.7	8.1
8 Years								
Trema	78,728	39,054	461	49.3	619	131.9	322.9	28.7
Psiadia C1	35,954	18,482	129	9.8	256	13.9	132.5	19.4
Psiadia C2	35,562	18,255	124	9.4	248	13.4	129.4	18.8
Psiadia C3	25,438	13,062	89	6.8	178	9.6	92.8	13.5
Rubus	24,188	11,438	113	21.0	94	49.0	120.7	16.8
Psiadia C4	10,750	5,525	39	2.9	76	4.1	39.6	5.8
Imperata	8,565	3,966	35	5.0	49	9.0	4.7	8.1

finally herbaceous fallows is not valid for the common fallow periods of 3–5 years in the study zone, but is only confirmed after 5 years and for longer fallow periods of 8–10 years. It is unlikely that farmers can depend on *Trema* as a major fallow species, because fallow periods of 8 years are no longer possible due to increasing land shortages and *Trema* disappears after the first cycle after deforestation. The upland systems in the Beforona-Vohidrazana area of eastern Madagascar rely therefore on shrub fallows for soil fertility restoration. Their AGB production, confirmed for the study zone by Brand and Pfund (1998), is often about half or less of biomass values reported from elsewhere in the humid tropics for similar fallow periods of 3 and 5 years (Snedaker 1980; Scott 1987; Uhl 1987; Fearnside et al. 2007).

Time needed for soil fertility restoration

When studying agricultural productivity and upland degradation dynamics in the Beforona-Vohidrazana area, Styger et al. (2007) learned that the time needed to restore soil fertility increases with each additional fallow cycle after deforestation and is not constant, as often discussed in the fallow literature (Van Reuler and Janssen 1993; Silva-Forsberg and Fearnside 1997; Brand and Pfund 1998; Kato et al. 1999). The findings of the study, based on land use history evaluation at plot level and through a joint analysis with farmers, indicate that for the first three fallow cycles after deforestation, a 3–5 year fallow period is judged sufficient by farmers to achieve a locally acceptable upland rice yield of 1.5–2 t/ha. But in the fourth fallow cycle after deforestation, the fallow
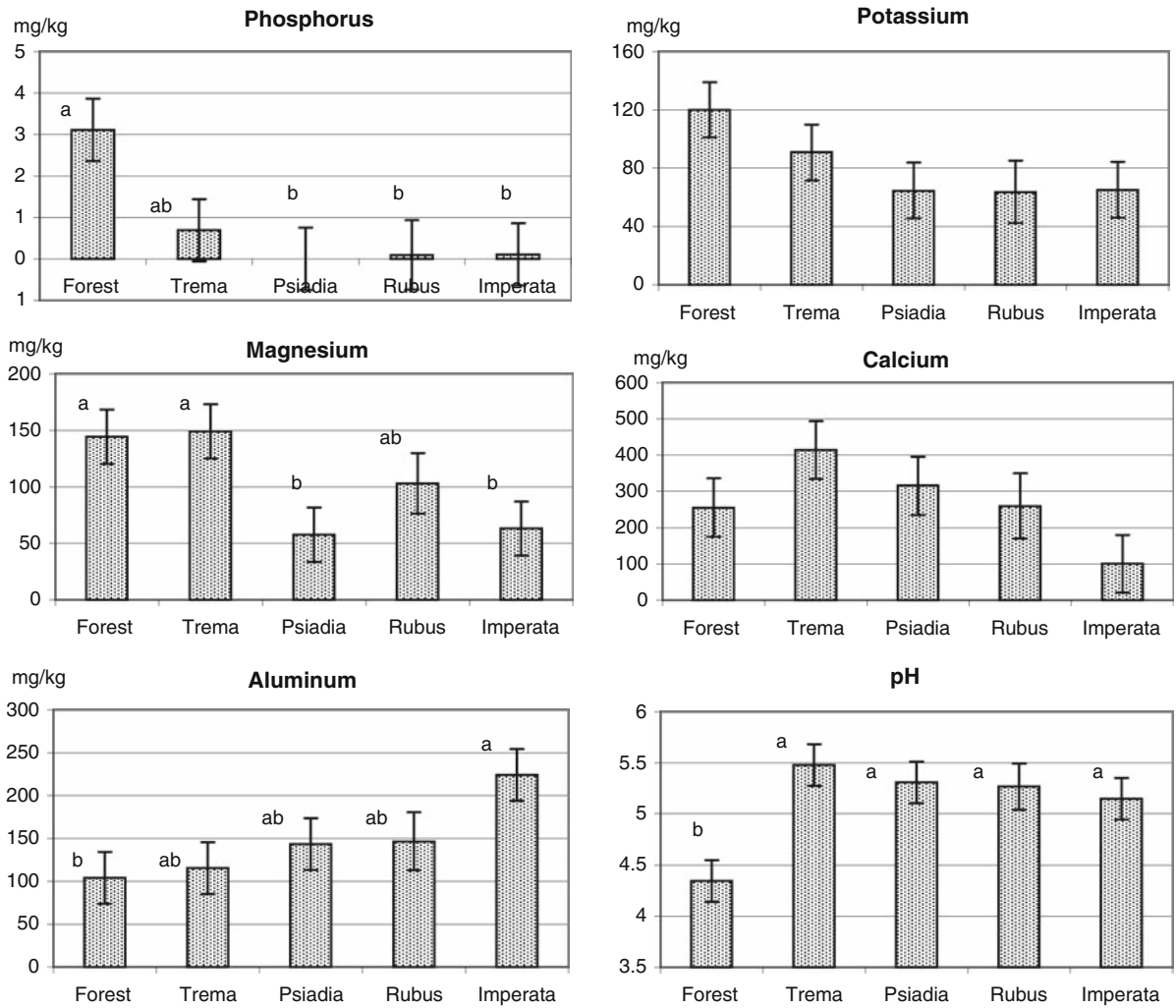
Fig. 5 Exchangeable soil nutrients (mg/kg) and pH (water) for rainforest and four fallow soils ($n = 5$ transects; adjusted Tuckey-Kramer test $P < 0.05$; 2 SE; Means that are followed by the same letter are not significantly different at $P < 0.05$)

period needs to increase to a minimum of 8 years, in the fifth cycle to 12 years and the sixth cycle to 20 years to produce a similar fallow biomass, with resulting comparative rice yields (Styger et al. 2007). The trend of this analysis can be confirmed when examining the fallow productivity of *Psiadia* in the four cycles after deforestation. In the first two *Psiadia* cycles, five-year-old fallows produced 20 t/ha of aboveground biomass. To obtain the same quantity, it takes 7 years in the third cycle and 17 years in fourth cycle. This corresponds approximately with farmers' appreciation of optimal fallow periods for the various cycles.

Aboveground carbon loss

The conversion of forest to upland cropping systems results in high carbon losses. Brand and Pfund (1998) estimated the carbon stocks of the rainforest vegetation at the study site to be 230 t/ha. Fallow above and below ground carbon stock at 5 years of age, was 14 t/ha for *Trema* (or 6% of forest values), about 11.5 t/ha for *Psiadia* C1, C2 and *Rubus* (or 5% of forest C), and 4 t/ha for *Imperata* (or 1.7% of forest C). The carbon loss calculated by Brand and Pfund (1998) was similar, with the most productive fallow, at 5 years, accumulating 10% and the grass fallow only 1% of the

rainforest's biomass. Uhl (1987) reports that after a slash and burn cycle in the upper Rio Negro region of the Amazon Basin a 5-year-old fallow reached 14% of biomass compared to the pre-existing rainforest.

Species adaptation to frequent slashing, burning and cropping

Soil fertility restoration depends on natural fallows in the *tavy* system. But none of the dominant indigenous and exotic fallow species in the Beforona-Vohidrazana area are able to withstand the management practices of cutting and burning at the current frequency. *Trema* and *Psiadia*, two pioneer species, depend on soil seed banks for propagation. As elsewhere in slash and burn agricultural systems, soil seed banks are progressively depleted, and tree seedlings are burned by recurrent fires (Uhl et al. 1981; Uhl and Jordan 1984; Cao et al. 1997; Cairns 2004). Under frequent disturbances, plant strategies for establishment and survival are shifting towards vegetative propagation (Hoffmann 1998). This is the case for two exotics *Rubus* and *Imperata*, which can propagate both sexually and vegetatively. *Rubus* resprouts from its root bulb, propagates through layering, and has bird-dispersed seeds. *Imperata* reproduces by airborne seeds and via vegetative rhizomes. Anemochory has shown to improve competitiveness of fallow species under high frequency slash and burn cycles further south in eastern Madagascar (Randriamalala et al. 2007).

Another plant adaptation mechanism to high disturbances is an increased allocation of energy and nutrients to root biomass (Uhl 1987). Several authors found an increasing root/shoot ratio with decreasing soil fertility (Jordan 1985; Vitousek and Sanford 1986). Uhl (1987) was able to show this relationship in a greenhouse experiment with *Cecropia* sp. and *Vismia* sp. *Rubus* and *Imperata* showed a much higher root/shoot ratio with 0.53 and 0.55 compared to *Trema* and *Psiadia* with 0.25 and 0.17, respectively. *Rubus* and *Imperata* showed also higher nutrient concentrations in roots and wood, compared to *Trema* and *Psiadia*. For instance, *Rubus* N root concentration (0.524%) was 126% of *Trema*'s and 215% of *Psiadia*'s. *Imperata*'s root P values (805 mg/kg) were double *Trema*'s and four times *Psiadia*'s root concentrations.

An additional survival strategy to advanced land degradation and nutrient poor soils is the relatively low nutrient concentration in leaves, indicating an improved nutrient use efficiency of the species (Uhl 1987). Leaf nutrient concentrations, especially for N and P, were highest in the early cycle fallows, and decreased with advancing soil use. *Rubus* N leaf concentration was 1.26%, and reached only 48% of *Trema*'s and 57% of *Psiadia*'s values, whereas for *Imperata*, with 0.48% of N in leaves, these values were 18 and 22%, respectively. Within species comparison shows concentrations that are relatively higher in leaves compared to roots and wood for early cycle species then for advanced cycle species.

With high root biomass and relatively higher nutrient concentrations in roots and wood compared to other species, *Rubus* not only achieved the highest nutrient stocks at 3 years, but also at 5 years of age, when total biomass of Psiada C1 and C2 was superior to *Rubus*. The presence of *Rubus*, especially in advanced degraded landscapes, can retain more nutrients over a longer time period then the native vegetation, thus acts like a nutrient 'sponge' in the landscape. Similarly, exotic, naturalized, and invasive shrubs have replaced the indigenous vegetation in many locations in the tropics. Among the species are *Chromolaena odorata* (de Rouw 1993; Roder et al. 2004), *Tithonia diversifolia* (Cairns 2004), *Mikania micrantha* (Ramakrishnan and Saxena 2005), and *Piper aduncum* (Hartemink 2001). These fallows can be labeled "improved fallows" if they restore soil fertility more rapidly than would the indigenous vegetation and at minimum labor cost to farmers. These exotics tend to colonize quickly, developing into thick stands protecting the soil, suppressing weeds, and producing a high biomass at young age, which appear to accelerate nutrient cycling and increase soil organic matter (de Rouw 1993; Styger and Fernandes 2006). Although not a nitrogen fixing plant, *Chromolaena*, for instance, has shown to have higher nitrogen, phosphorus, and calcium contents in its biomass compared with the indigenous fallow vegetation (Roder et al. 2004). On the other hand, these species can represent a threat to native biodiversity, with their invasiveness being difficult to control (de Rouw 1993; Roder et al. 2004).

Decline in soil nutrient availability

Available soil nutrients P and K were highest in forest soil, and declined rapidly with increasing

fallow cycles. Mg levels were similar under forest and *Trema*, and Ca levels rose temporarily under *Trema* to 163% of forest values, before both nutrients decreased with advancing soil use. At the same time Al concentrations increased. Soil pH rose sharply from forest soil to *Trema* from pH 4.35 to pH 5.48, followed by a gradual decline to pH 5.15 in *Imperata*. Our results are comparable to findings of Jordan (1989), who found an initial increase in Ca, Mg and pH after burning of forest biomass in San Carlos in the Amazon. Nye and Greenland (1960) noted an increase in pH from forest to fallow soil. With land use change from forest to agricultural land, Asio et al. (1998) observed on an Ultisol in Leyte, Philippines, that pH, Ca and Mg tended to increase, while soil organic matter, total and available N and K decreased. Nutrient decline, especially for available phosphorus, was correlated to decreasing soil organic matter in the Amazon (Jordan 1989). Nakano and Syahbuddin (1989) found that exchangeable bases, especially Ca, Mg and K are prone to leaching from surface soils, and were reduced where fallow vegetation is sparse and in wet climates. Hölscher et al. (1997) observed severe K losses of 45% in Northeast-Para in Brazil, which is similar to our findings where K, Mg and Ca were reduced to 43–59% of their original levels at the stage of *Imperata*.

Above and belowground nutrient losses

High nutrient losses are associated with the burning of biomass. Total element losses from burning and leaching have been reported by Mackensen et al. (1996), for C to be 94–98%, N 95–98%, S 69–76%, K 42–52%, P 30–47%, Mg 22–44%, and Ca 13–35%. Giardina et al. (2000) concluded that nutrient losses from slashing and burning were for N, P, Ca and K ca 97, 59, 50, and 43%, respectively. These nutrient losses are reinforced by some characteristics in the nutrient cycling processes of young fallows. In the early phase of a fallow, a net loss of nutrients from the topsoil is to be expected (Nakano and Syahbuddin 1989; Sanchez 1994). Plants tap soil nutrients and accumulate them rapidly in their biomass. It is only when litter fall greatly exceeds the increase of nutrient uptake into biomass, that the amount of nutrients in the topsoil may be restored (Sanchez 1994). In the *jhum* fallow system of northeastern India, soil nutrients decline under fallow for

5–10 years. Ramakrishnan (1989) estimates that a 10-year fallow period is the minimum in order to maintain the stability of the system. Furthermore, nutrients are unevenly distributed between soils and biomass. Most of the ecosystem's carbon and nitrogen stocks are located in the soil and the bulk of available P, K, Ca and Mg remain in the aboveground biomass (Sanchez 1994; Feldpausch et al. 2004). Additionally, not all nutrients restore at the same rate, and it varies greatly among the elements. Nitrogen, for instance, can be restored in less than 2 years, whereas calcium may need 15–20 years (Szott et al. 1999). In an Ultisol in the Peruvian Amazon, soil P and K were restored under a 4.5-year-old fallow, whereas Ca and Mg levels were still reduced by 25–40% (Szott and Palm 1996). Thus, as nutrients, especially available P, K, Ca and Mg, are accumulated in the vegetation during short fallow periods rather than in the soil, burning of fallow biomass contributes to the rapid depletion of nutrient stocks. It is therefore of great importance to develop fire-less farming system practices for the current *tavy* system that relies on short fallows.

Conclusions

Soil fertility restoration depends on natural fallows in the *tavy* system. But none of the dominant indigenous and exotic fallow species in the Beforona-Vohidrazana area are able to withstand the management practices of cutting, burning and cropping at the current frequency of 3–5 years, and eventually soils are abandoned for agriculture. As lengthening of fallow periods is not practical, there is a need to intensify and diversify the upland agricultural systems by restoring and preserving nutrient pools based on fire-less practices.

Optimizing management of organic matter inputs is a key principle to be developed. With the recycling of weeds and crop residues, currently exported, important nutrient pools can be retained within the plot. For example, approximately 70–80% of total K uptake remains in the shoots of rice. Thus, recycling the residues improves the availability of K, among other nutrients, which under slash-and-burn practices is quickly lost (Fageria 2001). Fire-free land management favors soil organic matter accumulation through periodic mulching, which reduces not only

nutrient losses, but improves the physical, chemical and biological soil properties (Denich et al. 2005). Increased soil organic matter content improves nutrient retention, contributes to pH buffering and decreases aluminum toxicity (Ludwig et al. 2001). Application of targeted inorganic inputs in addition to organic matter, such as rock phosphate, lime or chemical fertilizer, can complement key limiting elements such as P and Ca (Nandwa 2001).

With intensification efforts, the current rice-based upland system could be improved, for example, by integrating beans as a winter crop and ginger as a high value cash crop into the rotation. These crops are currently all planted on separate plots, depending on soil degradation level of the plots. By implementing a rotation, food and cash crops would benefit from the integrated nutrient management at the plot level and hopefully achieve a better production level than at present time.

A main pillar for developing a fire-less upland cropping system should be the integration of improved fallows. Elsewhere in the tropics, planted leguminous fallows, such as *Crotalaria* sp, *Calliandra* sp., have shown to be more effective, with faster accumulation of nutrients compared to the natural fallows, and having significant yield increasing effects for the subsequent crops, including upland rice (Akanvou et al. 2000; Niang et al. 2002; Barrios et al. 2005). Preferably, deep-rooted legume species should be selected for N fixation and nutrient capture from subsoils. Fast production of high quality litter enables quick return of nutrients to the soil, increases soil organic matter, protects soil surface and reduces weed pressure (Akanvou et al. 2000; Nandwa 2001). The combination of these practices should target the restoration and maintenance of the nutrients within the upland system, improve nutrient cycling and achieve sustained crop production.

With intensification measures at the plot level and with a fire-less regime, large sections in the landscape of the Beforona-Vohidrazana area would have the opportunity to develop into tree-based systems, creating a mosaic landscape with diversified agricultural and forestry systems. These can include (1) the extension and diversification of the traditional agroforestry systems based on coffee, banana and fruit trees, (2) the diversification of reforestation species allowing to produce various wood products, which have become rare as forest boundaries retreat further

and further, and finally (3) encouraging natural regeneration of native vegetation in strategic locations within the landscape, providing forest products to population, while at the same time fulfilling ecological services, such as enhanced above and belowground carbon sequestration, controlling soil erosion, protecting water sources, and conserving endemic biodiversity within the landscape.

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