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The impact of selective logging and forest conversion for subsistence agriculture and pastures on terrestrial nutrient dynamics in the Amazon

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The conversion of primary forests in the Amazon via selective logging, slash and burn agriculture, and pasture establishment, will continue because of the increasing demand for timber and agricultural land. Forest conversion has major impacts on the stocks and flows of essential plant nutrients. For example, the burning of slashed vegetation results in most of the carbon and nutrients in the biomass being volatilized during burning. Nutrient stocks are further depleted by the nutrient exports in timber and crop harvests. Poor crop and pasture management practices can result in rapid declines in soil fertility and reduced vegetation regrowth potential. These changes can influence the rate of secondary forest regrowth and carbon sequestration on abandoned crop and pasture lands. The dominant land use practices following forest conversion in the Amazon are identified and the data on the impact of selective logging, subsistence cropping, and extensive pastures, on nutrient stocks and budgets in terrestrial Amazonian ecosystems are reviewed.

A conversão de florestas primárias na Amazônia por meio de corte seletivo das árvores, derrubada e queima da vegetação seguida por cultivo e estabelecimento de pastagens irá continuar em função da crescente demanda por madeira e terras para agricultura. A conversão das florestas tem grande impacto nos estoques e ciclos de nutrientes essenciais para as plantas. Por exemplo, a queima da vegetação derrubada resulta na volatilização de substancial quantidade de carbono e nutrientes da biomassa. A exportação de nutrientes pela retirada dos troncos e colheitas das safras reduz ainda mais este estoque de nutrientes. Cultivos com baixa reposição de nutrientes e as práticas de manejo de pastagem podem

resultar em rápido declínio da fertilidade do solo e redução do potencial de recuperação da vegetação. Em áreas abandonadas após o cultivo e/ou pastagem, tais mudanças podem influenciar a taxa de crescimento da floresta secundária e o sequestro de carbono. Neste trabalho são identificadas as principais práticas no uso do solo após a conversão das florestas na Amazônia. Os impactos do corte seletivo das árvores, agricultura de subsistência e pastagens extensas nos estoques e balanços de nutrientes no ecossistema terrestre da Amazônia são revisados; deficiências no conhecimento existente são identificadas e importantes questões para a pesquisa são formuladas.

The principal causes of forest conversion in the Amazon have been subsidized cattle ranching and unsupervised small-scale agriculture. To a lesser extent, logging, road-building, hydroelectric development, mining, iron smelting and urban growth have also played a role (1). In recent years, se-

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lective logging and mining activities have increased dramatically, especially in the eastern Amazon (2). The nutrients contained in the soil and vegetation can be lost via burning, wood and crop harvests, soil erosion, leaching and gaseous emissions. The measurable costs of deforestation include the loss of biodiversity and of forest products, increased soil erosion, reduced soil productivity, flooding, siltation of hydroelectric facilities, and the release of carbon to the atmosphere.

In this paper, we review studies of nutrient cycling in primary rainforests, logged forests, and forest land converted to agriculture in the Amazon basin. We focus on the impact of selective logging, subsistence cropping and extensive pastures, on nutrient stocks and budgets in terrestrial Amazonian ecosystems. Nutrient and carbon dynamics in riverine ecosystems are treated in the companion paper by Richey et al (p 98). As plantations could become increasingly more important in the future, we also include a brief review and analysis of the available nutrient data on plantation forestry in the Amazon. We conclude with some key research questions.

Land use practices following forest conversion in the Amazon

Cattle ranching and subsistence agriculture are the dominant land use systems following forest conversion in the Amazon. The ranches are commonly over a thousand hectares in size. The vegetation is cut using machetes, axes and chainsaws, left to dry for two to three months and then burned. Next, seed of the pasture grass (*Brachiaria humidicola*, *B. brizantha*) is planted and livestock introduced when the pasture has been established. A combination of factors such as low native soil fertility, low carrying capacity of the pastures, excessive numbers of animals, and overgrazing, results in declining productivity of the pastures within six to eight years after establishment. Most of these pastures are usually abandoned and eventually return to secondary forest vegetation. The speed of colonization of abandoned pastures by tree and shrub vegetation is directly related to the intensity of their use as pastures. The greater the grazing pressure and/or period grazed, the slower the development of the fallow vegetation and therefore the recovery of site productivity (3,4). The easy availability of primary forest land and subsidies for pasture establishment on such land, has resulted in little secondary forest being used for the reestablishment of pastures. The withdrawal of subsidies for forest conversion to pastures in the early 1990s resulted in many of the ranchers investing in the recuperation of degraded pastures. For example, farmers plough up the old pasture, apply lime and fertilizers, and plant annual crops for a year before reestablishing pastures.

In colonization and settlement programs, landless families are usually given between 50 and 120 ha of primary rainforest land with the stipulation that they may deforest a maximum of 50% of this land. These farmers typically deforest up to two ha annually, burn the slashed vegetation, and plant

cassava (*Manihot esculenta*) for a year or two before abandoning the land to fallow vegetation. After about four years, the young fallow is slashed, the site is burned again, and the farmer plants corn followed by cassava for two to three years. It appears that slashing and burning the short four-year fallow vegetation, eases the burning and liberation of nutrients from the trunks and large branches remaining after the first burn. Estimates of the efficiency of burning range from 28 to 50% of the aboveground primary forest biomass (5,6), implying that between 150 and 200 Mg.ha⁻¹ of woody biomass remain unburned after the first burning. After the second burn, farmers may plant corn, cassava and perennial crops such as banana, cupuaçu (*Theobroma grandiflorum*), bixa (*Bixa orellana*) and citrus, before allowing the land to be colonized by forest species (7). Some farmers establish pastures soon after the first cropping phase, while others wait until the harvest of the crops planted after the second burn. Surveys in the states of Amazonas, Pará and Acre have revealed that in addition to being grazed by the farmer's livestock, these pastures may also be rented out to neighboring ranchers, or established with the specific objective of adding value to the property (8).

Agricultural productivity of the cleared lands usually declines rapidly after the first year of cropping due to a combination of decreasing soil fertility, increasing weed infestation, the use of unadapted crop varieties, and inappropriate management. The alternatives are to clear and burn more rainforest for new pasture/crops for another year or to adopt improved technologies that increase output per unit of land. The latter option normally requires greater labor and the use of inputs and usually results in farmers opting to continue the cheaper and less labor-requiring alternative of slash and burn cultivation or extensive, unmanaged pastures.

As described above, deforestation by small farmers is normally less destructive than conversion to extensive pastures and grazing. The cropped plots eventually return to forest via the processes of species succession. In some cases, however, repeated cycles of burning and cropping following short fallow periods, can result in soil degradation. Other associated practices could exacerbate the depletion of soil nutrients. For example, in the state of Pará small farmers in the Marabá region sell all unburned woody material from newly cleared and burned fields for charcoal making. The charcoal goes to the iron smelting industries in the state. Buschbacher et al (9) showed that unburned woody slash can be a significant source of P, Ca and K in pastures 8 years after clearing. We conservatively estimate that removals of unburned woody debris can result in a loss from the site of around 380 kg N, 8 kg P, 92 kg K, 61 kg Mg and 122 kg Ca per hectare. The derivation of these values is based on the assumptions that: 1) 80% of above-ground woody biomass (say 300 Mg ha⁻¹) is formed of trunks and coarse woody branches; 2) 40% of this biomass is consumed by fire; and 3) the nutrient contents of woody biomass (see Table 8) are representative for "terra firme" forests.

In recent years there has been a significant increase in logging of primary forests and the trend is for increased logging wherever there is access to the forest (see the white

paper by Nepstad et al, p 73). Logging has a direct effect on the nutrient cycle due to the nutrients exported in logs. Often, there is also an indirect effect via the negative impacts of the logging procedures on soil structure, bulk density, infiltration and water retention capacity.

Nutrients in upland soils of the Amazon

Nearly 75% of the Amazon basin contains acid, infertile soils classed as ultisols (Table 1) and oxisols (Table 2). Upland ("terra firme") soils such as oxisols, ultisols and some entisols and inceptisols, are characterized by low nutrient reserves, low effective cation exchange capacity (ECEC), high aluminum toxicity and low phosphorus availability (10). Of the 482 million hectares in the Amazon basin, 81% of the area had native pH values in the topsoil less than 5.3 and 82% had native pH values less than 5.3 in the subsoil. Associated with these low pH values is aluminum toxicity. While oxisols are likely to have very low levels of potassium, calcium and magnesium, ultisols may present greater problems of Al toxicity because of higher exchangeable levels of Al. The high levels of exchangeable aluminum in ultisols, some inceptisols, oxisols and spodosols can severely restrict root growth, nutrient uptake and hence nutrient cycling (11). Phosphorus fixation is usually high and hence P availability is low in oxisols. Sandy soils are especially low in nitrogen, although phosphorus, calcium and magnesium may also be low.

Cochrane and Sanchez (10) reported that 73% of the

soils in the Amazon basin have an aluminum saturation of 60% or more in the top 50 cm. Ninety percent of the soils in the Amazon have topsoil P levels less than 7 mg/kg, where crop and pasture yields can be expected to be low without additions of P. Approximately 16% of the soils in the Amazon are estimated to be strong P fixers, that is, they have over 35% clay and a high percentage of iron oxides. The low ECEC is also a soil constraint to plant productivity (12). The susceptibility of leaching of mobile nutrients increases as ECEC decreases. As soil nutrient contents are low and rainfall often exceeds potential evapotranspiration over much of the Amazon, it is critical that mobile nutrients added to the soil remain in the soil as long as possible giving the plant adequate opportunity to utilize them. For example, potassium which is highly mobile in the soil, is considered to be a constraint on 56% of the land area (10).

In comparison with rivers elsewhere, Amazonian surface waters are low in Ca, Mg, K and P (Richey et al in this volume, p 98) (13,14). The lack of these elements is due, in part, to the association of northern and southern Amazonia with the geologically ancient Guiana and Brazilian shields (15). Furthermore, central Amazonia has been exposed to several cycles of erosion and sedimentation which have resulted in the depletion of these elements from the sediments. Only western Amazonia, which received sediments from the Andean foothills, and the seasonally flooded varzeas (rivers banks) along rivers originating in the Andes, are richer in Ca, Mg and K.

It is important to note that upland soils in the Amazon can be highly variable. This variability extends from the soil order level to short-range variability occurring within a dis-

Table 1 - Properties of the typic paleudults (fine-loamy, siliceous, isohyperthermic) at Yurimaguas, Peru.

Depth (cm)	Org.			pH	Exchangeable				Effective CEC	Al saturation %	Bulk density Mg.m ⁻³	Porosity	
	Clay	Sand %	C		Ca	Mg	K	Al				Micro m ³ .m ⁻³	Macro
0 - 5	6	80	1.25	3.8	0.84	0.20	0.20	2.05	3.49	59	1.16	0.28	0.19
5 - 13	10	70	0.84	3.7	0.05	0.04	0.04	2.63	2.76	95	1.16	0.28	0.19
13 - 43	15	61	0.42	3.9	0.05	0.03	0.03	3.11	3.24	96	1.39	0.14	0.14
43 - 77	17	57	0.29	4.0	0.03	0.02	0.02	3.12	3.20	98	-	-	-
77 - 140	25	50	0.18	4.1	0.03	0.01	0.03	4.48	4.58	98	-	-	-
140 - 200	24	54	0.17	4.4	0.06	0.03	0.04	3.80	3.94	96	-	-	-

Source: Cochrane and Sanchez (10) and Alegre et al (72).

Table 2 - Properties of the xanthic hapludoxs (clayey, kaolinitic, isohyperthermic) at Manaus, Brazil.

Depth (cm)	Org.			pH	Exchangeable				Effective CEC	Al saturation %	Bulk density Mg.m ⁻³	Sat. Hyd. conductivity cm.h ⁻¹
	Clay	Sand %	C		Ca	Mg	K	Al				
0 - 8	76	15	3.0	4.6	2.00		0.19	1.1	3.29	33	1.04	28.1
8 - 22	80	12	0.9	4.4	0.20		0.09	1.1	1.39	79	1.12	8.1
22 - 50	84	8	0.7	4.3	0.20		0.07	1.2	1.47	82	1.11	9.6
50 - 125	88	7	0.3	4.6	0.10		0.04	1.0	1.14	88	-	-
125 - 265	89	5	0.2	4.9	0.10		0.11	0.2	0.31	65	-	-

Source: Camargo and Rodrigues (90) and Melgar et al (91).

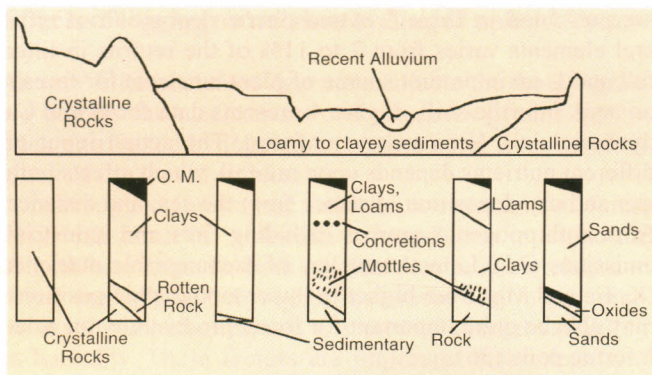


Figure 1. Schematic showing relationship between geology, landform and soils in a section of the Brazilian Amazon. Source: Reference 108.

tance of a few meters. An example of this variability is provided by examining representative soil profiles on a transect across the Amazon (Fig. 1). The mineralogy, texture, organic matter content, depth and degree of development all contribute to differences in soil chemical and physical properties. The old sedimentary basins and plateaus are commonly characterized by deep, mature soils. Less developed soils are found in recently denuded and recent sediment areas (16). In the dominant, deeply weathered oxisols and ultisols of the Amazon basin, the parent material may be generally inaccessible to plant roots. The productivity of forest vegetation on such soils is thus dependent primarily on a tight cycling of nutrients accumulated over a long period of time. Consequently, although the nutrients measured in drainage waters from catchments with deep, weathered soils may reflect the weathering of parent material, there may be little relationship between the nutrients in drainage waters and the nutrient dynamics of the vegetation cover (17).

Nutrient stocks and cycling in primary and mature secondary vegetation

Reviews of research on forest biomass (18,19), nutrients in litter (20) and mineral cycling (21) in the tropics, have shown that patterns of nutrient cycling in tropical ecosystems are diverse. The best studied nutrients are nitrogen, phosphorus, potassium, calcium and magnesium. These nutrients are also the most likely to limit primary production and other ecosystem functions (22).

Published estimates of total above-ground biomass of Amazon forests range from 227 to 394 Mg.ha⁻¹ (23,24), although direct measurements of forest biomass provide a much wider range of 143 to 666 Mg.ha⁻¹ (25). In a recent study of biomass and nutrients of four moist tropical forest sites in Pará and Rondônia, Kauffman et al (6) reported total above-ground biomass values

ranging from 290 to 435 Mg.ha⁻¹. The amounts of nutrients which are held within each compartment of a natural forest about 90 km north of Manaus, are given in Table 3. These data are compared with those from a similar soil in southern Venezuela (26) in Figure 2. The data confirm that the live vegetation is the dominant store of cations, and that the topsoil contains the largest stores of (total) nitrogen and (total) phosphorus (27). The soils are extremely deficient in phosphorus, especially in Manaus, and quite deficient in Ca, Mg and K. Total live biomass is higher at Manaus than in southern Venezuela, despite the lower phosphorus levels.

There is likely to be considerable variability among sites of nutrients in both soil and aboveground biomass. Kauffman et al (6) reported dramatic differences in both total nutrient pools as well as the partitioning of nutrients within pools at four different sites in the states of Pará and Rondônia (Fig. 3). The total aboveground pools of N ranged from 1401 kg.ha⁻¹ to 2427 kg.ha⁻¹, C ranged from 58 to 112 Mg.ha⁻¹, S ranged from 216 to 392 kg.ha⁻¹, P ranged from 56 to 87 kg.ha⁻¹, K ranged

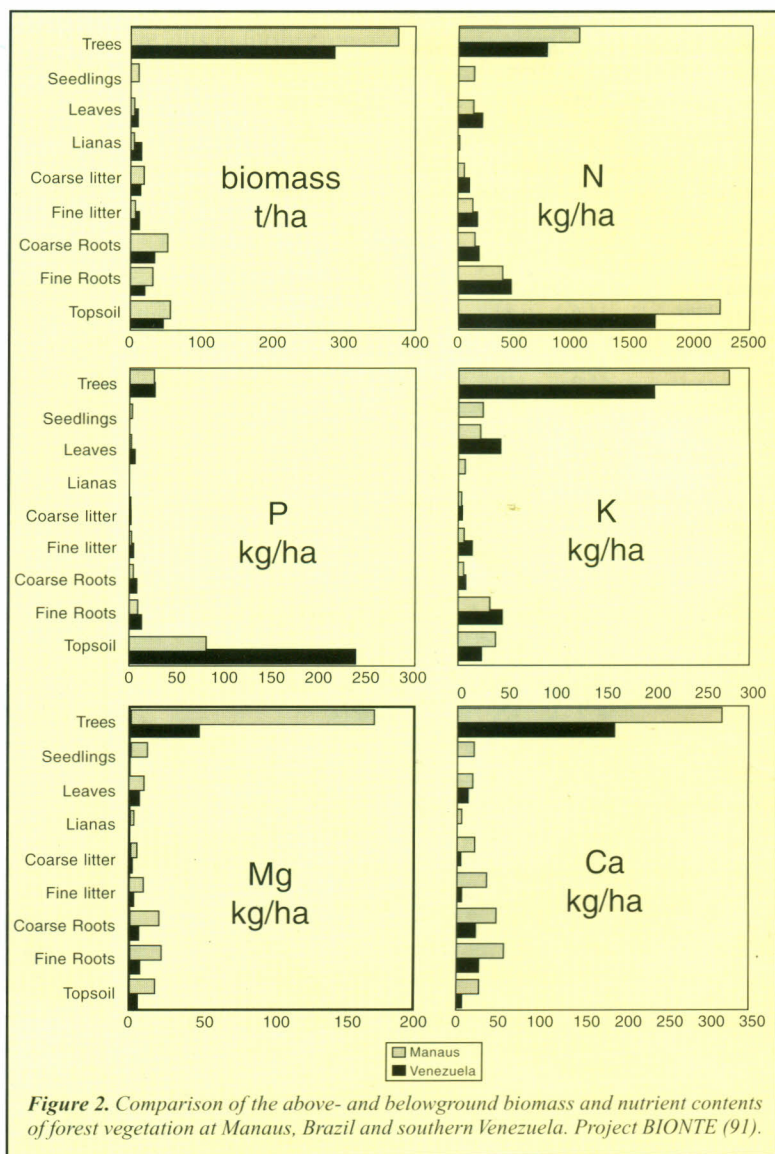


Figure 2. Comparison of the above- and belowground biomass and nutrient contents of forest vegetation at Manaus, Brazil and southern Venezuela. Project BIONTE (91).

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from 432 to 949 kg.ha⁻¹ and Ca ranged from 368 to 1274 kg.ha⁻¹. For comparison, data on carbon and nutrient pools from tropical lowland forests are presented in Table 4. Both P and Ca stocks tend to be significantly lower in Amazonian "terra firme" forests in comparison to the mean for tropical lowland forests. The popular belief that the vegetation is the main store of nutrients is clearly not true. The forest floor (litter, roots and topsoil) may contain from 50 to 80% of the nitrogen and phosphorus in the system.

Few published studies exist of nutrient dynamics in "terra firme" Amazonian primary forests. Klinge and Rodrigues (28) studied an upland forest near Manaus, Brazil. Data are also available for a Venezuelan forest on an oxisol which was studied by Jordan and Herrera (29), seasonally flooded "igapó" forests studied by Irmiler (30), and an Amazon "caatinga" forest in the upper Rio Negro (31,32,33). For most of these studies, however, the main emphasis has been on nitrogen dynamics.

Data on nutrient fluxes in tropical lowland forests (34),

are presented in Table 5. Atmospheric deposition of mineral elements varies from 7 to 11% of the returns in litter fall and is an important source of plant nutrients for forests on acid, infertile soils. Figure 4 presents data for N and Ca dynamics in a Venezuelan rainforest. The actual input of different nutrients depends upon rainfall, which affects both wet and dry deposition, distance from the sea, and distance from anthropogenic sources including fires and industrial emissions (35). Lateral transfers of exchangeable nutrients (K, Ca and Mg) from higher to lower topographic positions may also be quite important for forest productivity on acid, infertile soils (36).

In general, nitrogen, phosphorus and calcium in litter are mineralized within weeks or months, whereas the organic complexes in soil organic matter have turnover times of years to decades (37). In lowland tropical forests, the rapid turnover of N between soil and plant pools suggests that N is unlikely to be limiting to forest productivity (22,36,38). In contrast, P may be more generally limiting because of the low stock of P in most forests, low atmospheric inputs and fixation by iron and aluminum oxides (on oxisols and some ultisols). Potassium and magnesium rarely limit microbial processes (39) but are rapidly lost from decomposing litter and hence must be stored in plant biomass to prevent their depletion. It has been suggested that the growth of tree roots in litter may reduce leaching losses of nutrients by direct uptake of K, Mg and Ca (36,40).

Table 3 - Nutrient stocks in primary rainforest.

	DW	N	P	K	Mg	Ca
	t.ha ⁻¹			kg.ha ⁻¹		
Trunks	253.0	632.5	12.7	152.8	101.2	202.4
Coarse branches	80.8	234.3	6.5	72.7	32.3	72.7
Fine branches	44.6	147.2	5.8	49.1	35.7	40.1
Seedlings	10.4	81.1	2.6	22.9	12.5	19.8
Leaves	4.9	82.8	2.5	21.6	9.8	18.6
Coarse litter	18.6	53.9	0.6	1.9	5.6	20.5
Fine litter	7.0	126.7	1.3	4.9	9.8	35.0
Lianas	5.6	16.2	0.4	5.0	2.2	5.0
Coarse roots	51.9	150.5	4.2	4.7	20.8	46.7
Medium roots	16.3	163.0	5.5	19.6	11.4	32.6
Fine roots	4.5	55.8	0.6	4.1	3.2	9.0
Very fine roots	10.0	161.0	2.1	7.0	8.0	14.0
Topsoil	900.0	2250	81.0	36.0	18.0	27.0

BIONTE (92)

Table 4 - Carbon and nutrient pools for tropical lowland forests. Mean values are shown (with the range in parentheses).

	Organic matter (t.ha ⁻¹)	Nutrient pools (kg.ha ⁻¹)				
		N	P	K	Ca	Mg
Above-ground ^d	344 (185-513)	1334 (741-2430)	107 (27-291)	955 (277-3020)	1801 (424-3900)	288 (133-530)
Litter ^e	37 (5-74)	403 (137-672)	11.6 (2-18)	26 (8-46)	180 (21-569)	28 (18-57)
Roots	41 ^b (1.2-130)	442 (326-558)	12.3 (6-24)	96 (63-143)	561 (52-268)	49 (28-65)
Soil (0-30/50 cm)	230 ^c (90-370)	4581 (2600-6150)	406 (13-2470)	249 (58-399)	3579 (0-2220)	425 (17-2260)
% in forest floor	47	80	80	28	68	64

Sources: ^aProctor (34); ^bVogt et al (39) and ^cAnderson and Swift (93).

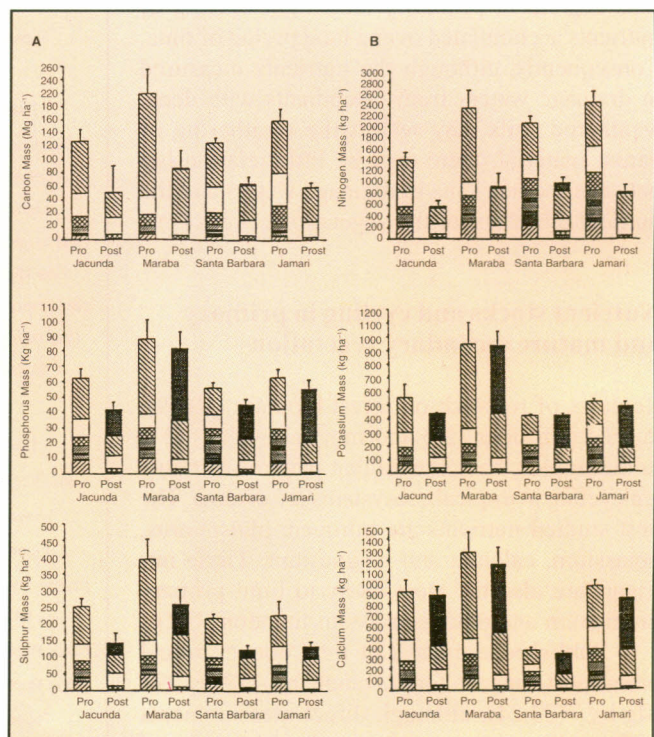


Figure 3. Nutrient pools of primary tropical moist forest slash before and after fires in Pará and Rondônia, Brazil. The vertical lines represent one standard error of the total nutrient pools. Litter is signified by rootmat by ■, dicots by □, attached foliage by ▨, wood debris 0-0.64 by ▩, 0.65-2.54 by ▧, 2.55-7.6 by ▦, 7.6-20.5 by ▥, >20.5 by ▤ and ash by ▣ (6).

Effects of logging on nutrient cycling of upland forests

As very little published data are available for the Amazon, we discuss the mechanisms and processes of nutrient cycling as affected by logging, using examples from other regions of the humid tropics.

In logged forests, the removal or reduction of forest cover can result in: 1) Increases in radiation inputs to the soil surface; 2) increases in incident precipitation relative to forest through fall; 3) higher maximum and lower minimum soil temperatures; and 4) increased diurnal variability in humidity. These factors are important determinants of

decomposition rates of litter and soil organic matter (SOM) and hence have a significant impact on nutrient dynamics. As a result, topsoil moisture, acidity and nutrient contents (41) and litter decomposition (42) are affected immediately after logging. Increased rainsplash, due to reduced canopy or litter cover, can destroy aggregate structure and increase soil erodibility (43) and nutrient removal via saturated overland flow and erosion (44). Very little is known about the amounts of dissolved nutrients washed away in runoff water. Nutrient removal associated with sediment load can however be significant. For example, in Sabah, Malaysia, the construction of logging roads led to peak suspended sediment concentrations being 3-8 times the peak concentrations recorded in the unlogged forest (45).

Although intensive logging in lowland tropical forests rarely results in the extraction of more than 10% of the total timber volume in the forest, the trees felled are usually dominant emergents with big crowns that cause considerable damage to the understory vegetation when they fall. In addition to the vegetation damage caused by felling, the construction of roads and skid trails to facilitate the extraction of timber results in further removal of vegetation and soil disturbance. Infiltration may decrease significantly on the main tracks, although some of these effects are probably short-lived (46). Logging also results in significant inputs of woody debris and leaf biomass to the forest floor. As much of this leaf material has not undergone senescence, it is likely to have higher contents of nutrients than leaf litter, and consequently may decompose and release nutrients much faster than senescent leaf litter. Where these nutrients are not taken up by the remaining trees due to root death from soil compaction

Table 5 - Carbon and nutrient fluxes for tropical lowland forests. Mean values are shown (with the range in parentheses).

	Organic matter (t.ha ⁻¹)	Nutrient pools (kg.ha ⁻¹ .y ⁻¹)				
		N	P	K	Ca	Mg
Rainfall: Input		15 (5-22)	10.9 (0.3-27)	11.6 (4-25)	13.9 (0-28)	3.6 (0.3-11)
Enrichment		32.5 (11.8-59)	2.7 (0.1-4)	113.6 (50-220)	25.9 (10-47)	20.9 (7-34)
Litterfall	9.3	149 (105-200)	7.3 (2-14)	64.6 (28-129)	137 (18-240)	32 (14-51)
Losses in streamwater	30	0.7 (1)	11.8 (1)	63.3 (9-15)	32 (2-163)	(2-51)

Source: Proctor (34).

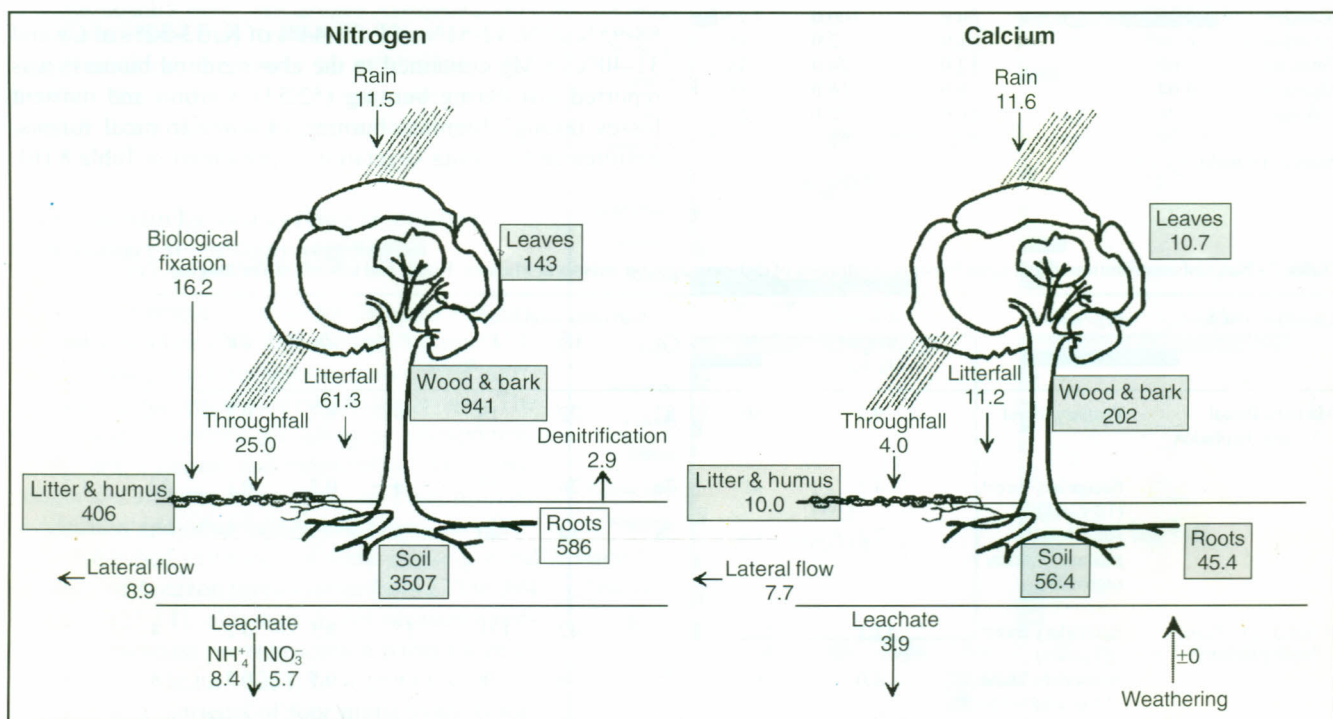


Figure 4. Schematic representation of N and Ca cycling in a "terra firme" rainforest. Numbers in boxes represent stocks in kg.ha⁻¹. Numbers with arrows are fluxes in kg.ha⁻¹.y⁻¹. Adapted from Herrera (31). Data from Jordan et al (109).

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and waterlogging caused by timber extraction, they may be lost by runoff, leaching and volatilization. The rapid regrowth and nutrient uptake by pioneer vegetation in the gaps and trails can minimize nutrient losses from the site.

In Asia, Whitmore (47) estimated that up to 55% of the forest was damaged by logging operations. Although fewer species may be logged in Amazonian forests as compared to the Asian dipterocarp forests, the damage to the remaining forest may still be quite high. For example, studies of damage to forests by commercial logging using the CELOS silvicultural system in Suriname (48) showed that the removal of 15 m³.ha⁻¹ resulted in 5% of the forest area being converted to trails and 20% as gaps, whereas a harvest of 46 m³.ha⁻¹ resulted in 18% of the area as trails and 38% as gaps. This was because when felling intensity is low, each felled tree creates its own gap and many skid trails are needed to extract scattered logs. At higher harvest intensities, felled trees are more likely to fall into existing gaps and skid trails can be used more intensively.

Logging affects the nutrient cycle directly via nutrient exports in harvested stems. The amounts of nutrients removed

depend on the harvest intensity (49). Estimates of nutrient exports for 3 typical intensities of selective logging are presented in Table 6. A harvest of 5 m³.ha⁻¹ is equivalent to a very selective harvest of 2 or 3 Mahogany trees, while removal of 50 m³.ha⁻¹ is recommended locally as the upper "safe" or sustainable harvest limit, and 100 m³.ha⁻¹ is typical for the high intensity logging practiced by the plywood industry. Nutrient exports from the low intensity logging are very low. N and P exports from the very intensively logged forest are low in comparison with total stocks in the topsoil. When a management cycle of 25 years is considered, the export levels are much lower than for the case of annual and perennial cropping systems. Very little work has been done to systematically document the nutrients extracted in log harvests and the subsequent impact on nutrient cycling.

Slash and burn agriculture and managed forest fallows

Traditionally, farmers in the tropics have temporarily overcome soil nutrient constraints to cropping by slashing and burning the forest vegetation. Farmers typically clear about a hectare of primary or secondary forest, burn it and then plant crops for one or more years. The quantities of nutrients accumulated in the forest biomass are typically in the range of 100-600 kg.ha⁻¹ for N, 10-40 kg.ha⁻¹ for P, 200-400 kg.ha⁻¹ for K, 150-1125 kg.ha⁻¹ for Ca and 30-170 kg.ha⁻¹ for Mg (27,50). Between 28 to 50% of the woody biomass burns to ash (6,24,51). Data from measurements of the nutrient contents of ash at various sites in the Amazon are presented in Table 7. Large losses of nutrients occur during the burn probably via the physical removal of ash via air currents generated during the burn. Approximately 88-95% of N, 42-51% of P, 30-44% of K, 33-52% of Ca and 31-40% of Mg contained in the aboveground biomass was reported lost during burning (52,53). Carbon and nutrient losses through biomass burning of some tropical forests, pastures and savanna vegetation is presented in Table 8 (6).

Table 6 - Biomass and nutrient exports for 3 scenarios of selective logging in comparison with total nutrients in topsoil (kg.ha⁻¹).

	Concentration (%)	Nutrients in harvested wood (kg.ha ⁻¹)			Nutrients in topsoil (kg.ha ⁻¹)
		5 m ³ .ha ⁻¹	50 m ³ .ha ⁻¹	100 m ³ .ha ⁻¹	
Stem dry weight (kg)	-	2,000	20,000	40,000	-
Nitrogen	0.25	5.0	50.0	100.0	2,250
Phosphorus	0.005	0.1	1.0	2.0	81
Potassium	0.06	1.2	12.0	24.0	36
Magnesium	0.04	0.8	8.0	16.0	18
Calcium	0.08	1.6	16.0	32.0	27

Source: Higuchi et al (49).

Table 7 - Nutrient contribution of ash upon burning rainforests of different ages on oxisols at Manaus, Brazil and ultisols at Yurimaguas, Peru.

Location and Soil	Vegetation	Ash dry weight Mg.ha ⁻¹	N	Nutrients additions							
				Ca	Mg	K	P	Zn	Cu	Fe	Mn
Manaus, Brazil Xanthic hapludox	Primary forest	9.2	80	82	22	19	6	0.2	0.2	58	2.3
	Secondary forest (12 years)	4.8	41	76	26	83	8	0.3	0.1	22	1.3
	Abandoned pasture (5 years regrowth)	2.2	18	58	14	40	3	-	-	-	-
Yurimaguas, Peru Typic paleudult	Secondary forest (25 years)	12.1	127	174	42	131	17	0.5	0.2	4	11.1
	Secondary forest (17 years)	4.0	67	75	16	38	6	0.5	0.3	8	7.3
	Secondary forest	1.1	10	217	51	81	8	0.7	0.1	2.7	3.4

Sources: Smyth and Bastos (94); McKerrow (53); Seubert et al (95); Sanchez (96); Smyth et al (97) and Smyth and Cassel (98).

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The effects of forest clearing and burning on soil chemical and physical properties can be summarized as follows: 1) The addition of nutrients contained in the ash to the soil, results in a decrease in soil acidity and aluminum saturation, and an increase in available P, Ca, Mg and K. These effects are reversed as time passes (Fig. 5) and the speed of reversal depends on the initial level of nutrients added in the ash, nutrient exports in crops, runoff and soil erosion, soil texture and rainfall; 2) topsoil organic C contents decrease due to higher surface soil temperatures, higher rates of decomposition, and lower levels of litter inputs relative to the forest; 3) if soil vegetation and litter cover is not rapidly replaced, both the amount and impact of rainfall reaching the soil surface is greater than under a forest canopy. Surface soil compaction and increased runoff and erosion can occur leading to the loss of nutrients from the site.

In a study of regeneration following deforestation in Amazonian "caatinga" forests, Uhl et al (54) reported that of the 336 kg.ha⁻¹ of N in the biomass, only 55, 33 and 3 kg.ha⁻¹ of N and 239, 64, 96 and 2 kg.ha⁻¹ of Ca were present 3 years after cutting, cutting and burning and bulldozing treatments. Jordan et al (55) found that while the total amount of soil N did not change from the conversion of "terra firme" primary forest to slash and burn agriculture, there was a net loss of 7% of the original forest stock per year due to harvesting, leaching and denitrification. Nitrogen from the decomposing slash contributed to the soil pool markedly decreasing N-fixation and increasing denitrification more than ten times.

Considerable quantities of nutrients may be exported in crop harvests. Table 9 presents data on yields and nutrient contents of some grain, seed, root and fruit crops commonly grown by small farmers in the Amazon. The actual

amount of nutrients exported from farmers fields are likely to be lower, as the yields shown are under plantation conditions. Traditionally, declining site productivity following deforestation and cropping, generally resulted in the site being abandoned and the establishment of fallow vegetation composed of forest species. Depending on the previous land use intensity and the soil chemical and physical properties, a site was left under forest fallow for periods of between 20 and 40 years prior to the secondary forest vegetation being cut and burned and cropping resumed. The accumulation of nutrients and shading out of weeds by the regenerating forest vegetation, and the action of roots and associated microorganisms and fauna are the processes by which the potential soil productivity of the abandoned site is gradually improved to a state approaching that of a primary rainforest. On acid, infertile soils, the establishment, growth and recuperation of site productivity by natural forest fallow vegetation may take as long as 50 to 60 years.

Szott et al (56), have studied managed fallows of fast-growing, N-fixing and other nutrient accumulating species. Sanchez et al (57) identified *Gmelina arborea* as an accumulator of Ca and Mg. Stands of *Heliconia* spp and *Gynerium* spp had three to four times as much phosphorus as natural fallow species of the same age in P-deficient inceptisols (58). Organic phosphorus is the most important source of phosphorus in highly weathered tropical soils (59). Incorporation of fast-growing trees into managed fallows offers the potential to increase this organic P pool. In a study of bush fallows, Tiessen et al (60) found a 28% increase of organic P in the soil but only a 9% increase in total P during a 10 year bush fallow. There is even some evidence that some species are able to utilize insoluble forms of soil P not utilized by crop species (61).

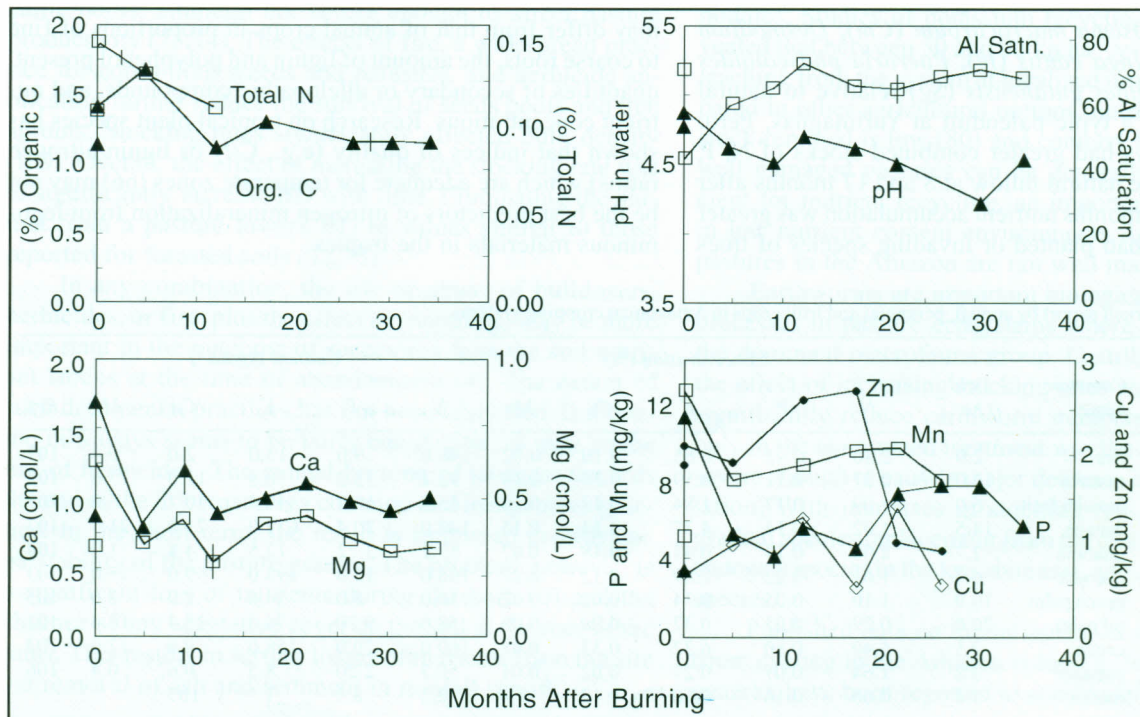


Figure 5. Changes in surface soil (0-15 cm) fertility parameters for an ultisol in Yurimaguas, Peru, during 3 years of cultivation following slash and burn clearing of an 11-year-old secondary rainforest. From Smyth et al (110).

Table 8 - Carbon and nutrient losses through biomass burning of selected tropical ecosystems.

Site	C (Mg.ha ⁻¹)	N	P	K (kg.ha ⁻¹)	Ca	S	Source Ref.
Cerrado, Brazil Tropical dry forest, Brazil	2.6-3.3	22-26	0.8-1.6	5.8-7.9	4.7-10.8	3.0-4.2	99
Catte pastures, Brazil	25-32	428-530	1-21	nd	nd	nd	100
Tropical secondary forest, Brazil	11-21	205-261	1-11	11-33	0-16	16-25	6
Tropical primary forest, Pará, Brazil	22-47	206-587	2-20	20-95	10-124	27-44	6
Tropical primary forest, Rondônia, Brazil	76-112	816-1387	6-20	8-111	30-108	109-137	6
	58-100	1064-1605	8-11	3-36	30-99	92-122	6

nd = data not collected; adapted from Kauffman et al (6).

(*Ie, Do*), than in treatments that had herbaceous species. Quantities of aboveground N in the leguminous fallows exceeded that in the natural woody fallow at all sampling dates. After 53 months of regrowth, the aboveground biomass ranged from 8 t.ha⁻¹ (*Ca*) to 63 t.ha⁻¹ (*Ie*) fallows with large numbers of trees accumulating a total net mass of between 12.4 and 16.2 t.ha⁻¹.

Positive effects of fallows on crop yields could be due to: 1) Remobilization of nutrients from hitherto unavailable to available forms; 2) nitrogen input into the soil through biological nitrogen fixation;

Improved fallows could be established by: 1) Allowing certain valuable trees and shrubs to grow at the expense of others; and/or 2) planting with desirable trees as the land enters into a fallow phase (62,63). The potential benefits of such managed fallows include: a) The enrichment and enhanced conservation of site nutrients; b) the rapid reduction of the seed pools of future weed species, and c) the provision of economically valuable products to tide the farmer over until the productivity of the site has been restored by the fallow (7). In a study of six traditional systems of managed fallows, Kass et al (64) concluded that evidence for biological enrichment of soil caused by the fallow was inconclusive. Apparently the farmers used the fallows for their economic rather than biological values.

There are few estimates of the accumulation of above- and belowground and litter mass for secondary vegetation in the Amazon. Szott et al (56) compared biomass and nutrient accumulation among managed fallows of *Cajanus cajan* (*Cc*), *Centrosema macrocarpum* (*Cm*), *Desmodium ovalifolium* (*Do*), *Inga edulis* (*Ie*), *Pueraria phaseoloides* (*Pp*), and *Stylosanthes guianensis* (*Sg*) relative to natural woody fallows on a typic paleudult at Yurimaguas, Peru. The planted fallows had greater combined stocks of N, P, Ca and Mg than the natural fallow at 8 and 17 months after planting, but by 29 months nutrient accumulation was greater in treatments that had planted or invading species of trees

3) cycling deep soil nutrients back to the crop root zone; 4) improving soil physical properties by organic matter addition and root activity, and 5) binding of toxic exchangeable aluminum by organic matter in acid soils. The actual contribution of the fallow vegetation to the nutrient pools of the soil needs to be separated from the effects of the rest period per se.

The quality of organic inputs is one of the factors that influences the rate of decomposition and release of nutrients from organic residues. The presence of different tree species with litter of different qualities could impact the short- and long-term storage and mineralization of carbon and nutrients. Nitrogen release patterns may be more closely related to tissue polyphenolic contents than to lignin or nitrogen contents or lignin/nitrogen ratios (65). In general, on fertile soils, leaf litter quality is higher and decomposition faster than on acid, infertile soils (22). Very little is known about the quality of root litter. Root litter from trees may differ from that of annual crops in proportions of fine to coarse roots, the amount of lignin and polyphenol present, quantities of secondary or allelopathic compounds, and nutrient concentrations. Research on tropical plant species has shown that indices of quality (e.g., C/N or lignin/nitrogen ratios) which are adequate for temperate zones (66) may not be the best predictors of nitrogen mineralization from leguminous materials in the tropics.

Table 9 - Potential nutrient export by annual, perennial and fruit crops in Amazonian cropping systems.

Species	Common name	Yield (t.ha ⁻¹)	Concentration (%)					Content (kg.ha ⁻¹)					Ref.
			N	P	K	Ca	Mg	N	P	K	Ca	Mg	
<i>Oryza sativa</i>	rice	2.0	2.30	0.45	0.65	0.10	0.02	46.0	9.0	13.0	2.0	0.4	101
<i>Manihot esculenta</i>	cassava	12.0	0.27	0.11	0.59	0.10	0.13	32.4	13.2	70.8	12.0	15.6	102
<i>Passiflora edulis</i>	passion fruit	6.0	1.09	0.17	1.84	0.17	0.10	65.4	10.2	110.4	10.2	6.0	103
<i>Musa</i> sp	banana	14.5	1.02	0.14	4.37	0.14	0.15	148.0	20.4	633.0	21.0	21.7	103
<i>Paulinia cupana</i>	guaraná	2.7	2.00	0.14	0.47	0.18	0.07	53.2	3.72	12.5	4.8	1.9	104
<i>Cocos nucifera</i>	coconut	6.7	1.61	0.22	2.89	0.13	0.22	108.0	15.0	193.0	9.0	15.0	103
<i>Bactris gasipaes</i>	peach palm	10.0	1.10	0.05	0.34	0.02	0.02	110.0	5.0	34.0	2.0	2.0	105
<i>Elaeis guineensis</i>	oil palm	20.0	0.29	0.05	0.37	0.08	0.08	58.0	9.20	74.0	15.4	16.4	101
<i>Theobroma cacao</i>	cocoa	2.5	6.40	0.80	6.32	0.32	0.48	160.0	20.0	158.0	9.0	12.0	103
<i>T. grandiflorum</i>	cupuaçu	3.2	1.64	0.07	0.27	0.02	0.01	50.7	2.20	8.5	0.6	0.4	106
<i>Hevea brasiliensis</i>	rubber	1.4	0.68	0.16	0.60	0.12	9.4	2.3	8.3	1.7	107		

Extensive pastures

For a variety of agricultural, social and economic reasons, pastures are the preferred agricultural system of both large and small land holders (67). Once cut, an estimated 70% of tropical forests in Amazonia ends up in pastures (68). Such pastures may contain native volunteer species, planted unadapted species, and/or poorly managed adapted species. The lack of management eventually results in soil and pasture degradation and low animal productivity (3,69).

Pasture degradation probably commences with overstocking which in turn leads to overgrazing, increased trampling, and poor vegetative cover of the soil surface. Certain soil macrofauna groups may be lost (70), resulting in a dominance of a few groups which may promote a deterioration of soil structure and actually increase soil compaction (71). The widespread practice of annual pasture burning to improve pasture quality and reduce pests also results in the soil surface being left bare for several weeks. In addition to the nutrients lost during the burn, surface runoff and soil erosion increase resulting in further nutrient transport out of the pasture. The declining availability of nutrients results in poor pasture regrowth and more overgrazing as animals seek to compensate for lower available forage quantity. With very low animal live weight gains and increasing animal mortality, pasturing becomes uneconomic and the pasture is abandoned.

The method of rainforest clearing is extremely important to the future regrowth potential. Bulldozer clearing, for example, can cause long lasting negative effects on crop or pasture productivity because of the removal of topsoil and soil compaction if no efforts are made to rectify the resulting poor physical and chemical conditions (72). Trampling in tropical pastures causes some degree of soil compaction since the soil is generally moist and constantly subjected to cattle hoofs, although not severe enough to affect pasture productivity (73,74). The effects of fire, a widespread practice for controlling weeds and parasites, and herbicide application further reduce the survival of seeds pools and tree sprouts. Stocking rates significantly affected bulk density (BD). Overall, the effect of increasing the stocking rate was to significantly increase BD with time. Eliminating the animal from a pasture lowers BD to values similar to those reported for forested soils (12,75).

In any combination, the use or abuse of bulldozers, herbicides, or fire, plus the effect of trampling, may be more important in the outcome of succession than the soil nutrient stocks at the time of abandonment (4). The extent of such detrimental practices has not been identified. Bulldozing nowadays seems to be fairly uncommon, as may be the use of herbicides. The annual burning of pastures towards the end of the dry season is a common and inexpensive practice. In the short term, the result is improved growth and palatability of the pasture grasses. The problem, however, is a significant loss of nutrients during the burn (6) and the absence of any vegetative cover on the soil at the start of the rains. This results in further losses of nutrients from the site via removal of ash and sediment in rainfall runoff.

The results of several studies have shown that following forest burning and grazing, most chemical parameters, except for available P, can remain fairly stable for 6 to 10 years (3,73,76,77,78) and should not limit pasture productivity. Generally, P availability has been found to decline with time and may be the most limiting element to pasture productivity, followed by N in the more humid areas (57,69). Decreases in available K, Ca and Mg due to leaching have been reported for pastures on an oxisol in Manaus (73,78). The amount and rate of movement in Ca and Mg to lower soil depths were relatively small and slow, and only became significantly different from the forest control after 6 years of grazing. Potassium movement, however, was quite rapid after burning (4 months) but was dependent on the magnitude of K input and the pasture stand density. In bare plot controls, high K losses (below 1 m) were detected in an ultisol only if rates as high as 300 kg.ha⁻¹ were applied to bare plots, while at lower application rates, K was retained at a soil depth of between 5 to 40 cm. There was a significant reduction in K leaching if the pasture was in place, illustrating the importance of the plant in nutrient conservation (3,74).

In an experiment in the humid tropics near Pucallpa, Peru, Ara and Sanchez (79) reported that when associated with the grass *Brachiaria decumbens*, the herbaceous legume *Desmodium ovalifolium* contributed the equivalent of 206 kg.ha⁻¹ of N to the total N yield of the sward. The association of *D. ovalifolium* with the grass significantly improved the N quality of the diet with the grazing animals averaging 226 kg/ha/y of N intake and an estimated 187 kg.ha⁻¹.y⁻¹ of N returned to the soil via excreta. A certain portion of the N fixed by the legume is transferred to the associated grass via: 1) Ingestion of the legume by the animal and transfer of the N to the grass via dung and urine; 2) legume leaf litter; and 3) decomposition of legume roots and nodules. Studies of potassium recycling under grazing revealed that between 30 and 90 kg.ha⁻¹.y⁻¹ of K were lost via leaching from the system at localized urine spots (74). Compared to other agricultural options, nutrient export by livestock removal is low (80) and contrary to common beliefs, well managed pastures can be generally regarded as efficient for nutrient recycling, an important feature specially in low nutrient content environments. Unfortunately, most pastures in the Amazon are not well managed.

Earthworms are important biological mediators of soil processes in pasture ecosystems where they are generally the dominant macrofauna group. Castilla (70) showed that the effect of increasing stocking rates was to gradually and significantly reduce earthworm numbers and biomass, but only in the overgrazed treatment was the effect of trampling severe enough to cause a major decrease in earthworm population. With increases in stocking rate, there was also a gradual species replacement from the dominant, soil dweller, endogeic species to the less abundant, surface dweller, epigeic species.

Published data on the influence of macrofauna on nutrient cycling in the Amazon is hard to find. Earthworms in general, have been reported to accelerate the organic matter

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cycle by increasing both mineralization and humification. This results in a decrease in the mean residence time of C in the soil and better mixing of organic compounds throughout the soil profile (81). In the tropics, earthworms have been reported to ingest up to 1200 Mg.ha⁻¹.y⁻¹ of dry soil (82) and produce large quantities of readily assimilable organic matter in the form of mucus. In a tropical pasture from Mexico, a population of *Pontoscolex corethrurus* was reported to ingest ca 300 Mg soil annually and excreted as much as 50 Mg.ha⁻¹ of mucus. This mucus was found to contain 3% N implying a large N flux through the earthworm biomass (83). The cutaneous mucus deposited on the burrow walls is known to have a significant, though still poorly quantified, effect on microbes and other soil macrofauna groups (84).

Pasture abandonment leads to plant succession. The speed of forest recovery depends on the previous intensity of pasture use, a critical factor determining the availability of regenerating germplasm. A secondary forest can be established quickly after pasture abandonment if high intensity practices such as bulldozing, herbicide application or chronic fire has not been used (85,86). Some native species (*Vismia* spp, *Cecropia* spp) have the ability to rapidly colonize degrading pastures (53). It is not known, however, whether the ease with which such species colonize degraded sites is related to their ability to form effective symbioses with native mycorrhizae, or their ability to tolerate high levels of toxic aluminum, or whether they have alternative strategies for nutrient uptake at very low available levels in the soil.

Forest and tree crop plantations

Relatively few timber plantations have been established in the Amazon. In a study of nutrient cycling in forest plantations at Jari in the state of Pará, Russell (87) reported that at the end of the first rotation, *Pinus caribaea* (9.5 years) and *Gmelina arborea* (8.5 years) plantations had between 40 and 60 percent of the total plant biomass of the original primary forest. The plantations contained approximately 60% of the total N stock of the primary forest with the bulk of the N losses occurring at clearing of the original rainforest. As none of the trees were legumes and no legume cover crops were used, no N build up occurred.

The plantation species were efficient at conserving P, with nutrient stocks ranging from 76 to 116% of the rainforest values. Decreases in P stocks at the start of the second rotation could largely be accounted for by the P exported in the first rotation harvest. The replacement of primary forest vegetation with plantation species resulted in 68% of the K being lost first by rapid leaching following the clearing phase of the primary forest, and later via export in the first rotation timber harvest. Calcium stocks decreased to around 56% and magnesium to about 75% of the primary forest levels. Losses could be accounted for by the amounts removed in timber harvests and the small amount of Ca leached. The negative effect of plantations on nutrient stocks occurs during the establishment phase of the plantations. This is prob-

ably due to the high levels of soil disturbance brought about by forest clearing methods, and also because the soil is left exposed for longer periods of time than soil under crops or pastures.

Research issues on terrestrial nutrient cycling in the Amazon

The dominant land use practices in the Amazon continue to be extensive pasturing, deforestation for subsistence cultivation, and selective logging. Subsistence farmers initially burn primary forest but prefer to slash and burn forest fallow vegetation due to the smaller quantity of biomass present and the lower labor required to slash this type of vegetation. Given the population growth rate and lack of access to farm land in southern and northeastern Brazil, spontaneous migration to the Amazon is likely to increase significantly in the future. Although land use policy changes have stopped subsidized deforestation for pasture establishment, Fearnside (88) has reported that the bulk of deforestation and burning in recent years is still occurring in areas where there are large areas of pasture. The continued practice of extensive pasturing, will eventually result in pasture degradation and abandonment. In some cases, ranchers are practicing selective logging in order to obtain the cash for rehabilitating degraded pastures or intensifying extensive pasture operations. In such intensification operations, the use of lime, fertilizers and mechanization will have major impacts on nutrient dynamics and cycling. Whether these impacts are negative or positive will depend on the soil, crop and/or pasture management strategies used.

Farming, ranching, logging and mining activities will continue to have significant impacts on the existing forest resource in the Amazon (see Nepstad et al, in this volume, p 73). Relatively little is known, however, about the impacts of forest conversion for other land uses on terrestrial nutrient dynamics in the Amazon. Much of the deforestation for agriculture and pastures is occurring because of poor land management practices that result in severe negative impacts on nutrient cycling and a rapid decline in soil productivity. Furthermore, the rapid loss of terrestrial nutrients at the local scale can have negative impacts on the productivity of local and regional aquatic resources. To improve our knowledge and understanding of the impacts of forest conversion and subsequent land use on terrestrial nutrient dynamics, we pose several research questions that need to be addressed:

- How do deforestation and burning affect the availability of macro- and micronutrients and the dynamics of these nutrients in: 1) Planted pastures; 2) during subsistence cropping; 3) after pasture abandonment; and 4) during forest regeneration? More information is also required on the nutrient dynamics of intact forest so that we can better quantify the impact of forest conversion on carbon and nutrient transfers among terrestrial and aquatic ecosystems and the atmosphere.

- What are the key soil, water, microclimatic and biotic factors that influence the regrowth of secondary forest vegetation in: 1) Natural treefall gaps; 2) logging gaps; 3) abandoned subsistence agriculture sites, and 4) abandoned pastures?

- What are the effects of selective logging, deforestation for subsistence agriculture and pastures, and secondary forest regrowth on soil organic matter (SOM) dynamics? Studies on SOM fluxes should distinguish among fractions of SOC based on the activity or response of these fractions to management factors (89).

- What is the impact of forest conversion on soil fauna dynamics and the contribution of the different soil macrofauna groups in sustaining soil productivity under subsistence cropping and pastures? Soil macrofauna is known to have a significant impact on litter transformation, soil organic matter and nutrient dynamics. Can groups of soil macrofauna be identified and predictive relationships developed between the functioning of these groups and soil quality?

- Phosphorus is probably the major limiting nutrient in the acid, upland soils of the Amazon. What are the plant attributes (e.g., extensive roots, deep roots, tolerance to aluminum toxicity, symbioses with mycorrhizae) that characterize those species able to colonize disturbed sites and accumulate nutrients and carbon? Are mycorrhizal symbioses more prevalent in secondary forest regrowth than in primary forest?

- What is the effect of increasing plant available P by adding P fertilizer, on rates of net primary productivity and C accumulation in primary and secondary forests and pastures.

- Are the many native species of legumes in primary and secondary forests active in nitrogen fixation even at low levels of available soil P? If yes, we need to reevaluate interpretations of conventional soil nutrient tests for acid-tolerant, native forest germplasm. ■

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