Potential of Brazilian Amazon Soils for Food and Fiber Production

Adônis Moreira[1*] • Nand K. Fageria[2**]

[1] Cattle-Southeast Center of EMBRAPA, São Carlos, São Paulo State, Caixa Postal 339, CEP 13560-970, Brazil

[2] National Rice and Bean Research Center of EMBRAPA, Santo Antônio de Goiás, Goiás State, Caixa Postal 179, CEP 75375-000, Brazil

Corresponding author: * adonis@cppse.embrapa.br   ** fageria@cnpaf.embrapa.br

ABSTRACT

The Amazon region has the world's largest tropical forest. Its conservation is of high importance to maintain the balance of climatic conditions and the diversity of the flora and fauna of this still largely unexploited region. In view of the increasing concern for the environment and growing world demand for food and fiber, and since this regions represents one of the last agricultural frontiers, there is a need for sustainable management to produce food and fiber. The objective of this review is to discuss the region's potential and the problems related to the use of these areas caused by anthropogenic activities. Brazilian environmental laws permit the use of Amazon up to 20% of its total territory. The Amazon region contains extensive savanna areas, with eutrophic soils, and 6.0 million hectares floodplains. However, the majority of soils are characterized by high acidity and low nutrient availability (0.4 billion ha – 86% of the area), and in the primary forest the dynamic of organic matter is responsible for recycling nutrients. Unfavorable climate conditions in the humid tropical part, with periods of intense rainfall and flooding, restricting cultivation of annual crops, is another problem of the region. In the more elevated upland regions, where the climate is more favorable, the planting of exotic and native tropical fruit species in combination or monoculture has great productive potential.

CONTENTS

INTRODUCTION

The Brazilian Amazon covers an area of about 5.0 million km² (0.5 billion ha), which represents 60% of the country's territory (Rodrigues 1996). The states which make up part of Amazon are Acre, Amazonas, Rondônia, Mato Grosso, Amapá, Tocantins and Pará, along with the western part of Maranhão State. It constitutes the world's largest reserve of land which can be used for production of food and fiber.

In strategic terms, despite laws that permit use of only 20% of the area, there are still extensive tillable lands (12% of the soils are eutrophic). Other factors contribute to the expansion of the primary sector in the region are hydroelectric potential, estimated at 70 million kW, over 40% of Brazil's total estimated potential; the vast hydrographic system, with some 19,000 km of permanently navigable rivers, particularly the Amazon River Basin (Pandolfo 1979); and the low population, estimated at 15 million people, for a population density of three inhabitants per km² (IBGE 2000).

Occupation of the region has mainly been occurring along the highways, especially the Belém-Brasília - BR 153, Cuiabá-Santarém - BR 163, Transamazônica - BR 230 and Cuiabá-Porto Velho - BR 364 (Becker 2001). Currently the deforested area extends over approximately 65.16 million

Table 1 Estimates of agricultural activities associated areas in Brazilian Amazon.

Activities	Area (thousand ha)
Pasture non-degraded	35,000
Pasture degraded	17,500
Secondary vegetation (Savanna)	25,000
Perennial crops:	1,060
Coffee	230
Reforestation	130
Rubber	60
Cacao	100
Oil palm	60
Cocoa	25
Cupuassu	25
Piper nigrum	20
Peach palm	5
Annual crops:	10,000
Soybean	5,700
Rice, cotton, bean, maize, manioc, etc.	4,300
Others	600

Source: Modified from Sá (2005)

Mini-Review

Table 2 Chemical proprieties of floodplain soils - Madeira, Solimões and Amazonas rivers Amazonas (AM) and Pará State (PA).

Municipalities	pH	P	K	Ca	Mg	Al
	H$_2$O	------ mg kg^{-1} ------			----------- cmol$_c$ kg^{-1} ------------	
Barreirinha (AM)[1]	4.7	32	92	3.7	2.6	2.5
Castanho (AM)[1]	5.9	92	139	9.4	3.5	0.4
Careiro da Várzea (AM)[3]	6.4	-	90	12.5	2.8	0.1
Iranduba (AM)[2]	5.9	116	130	11.5	2.3	0.2
Manacapuru (AM)[1]	5.2	84	108	9.7	3.0	0.6
Manaquiri (AM)[1]	4.7	39	91	9.0	2.3	2.9
Parintins (AM)[1]	4.9	206	61	5.1	3.0	1.9
Coari (AM)[4]	5.0	104	166	9.7	2.2	0.1
Tabatinga (AM)[4]	6.0	7.3	134	2.0	2.5	0.1
Alenquer (PA)[5]	4.5	24	92	8.0	1.1	3.4
Óbidos (PA)[5]	5.9	9	104	3.6	0.9	0.1

Sources: [1] Embrapa (1984a); [2] Cravo *et al.* (2002); [3] Alfaia and Falcão (1993); [4] Moreira, A. (unpublished); [5] Embrapa (1984b).

Table 3 Distribution of main soil types in the Brazilian Amazon.

	Soil classification		Brazilian Amazon	
Brazilian	**American**	**FAO**	**km^2**	**%**
Dystrophic (V% < 50%)				
Latossolos	Oxisols	Ferralsols	2,097,160	40.87
Argissolos	Ultisols	Acrisols	1,559,850	30.40
Plintossolos	Alfisols, Oxisols, Inceptisols	Luvisols Eutric, Nitosols	359,650	7.00
Espodossolos	Spodsols	Podzols	99,950	1.95
Gleissolos	Entisols	Gleysols	44,050	0.86
Neossolos	Entisols	Regosols	246,540	4.80
Eutrophic (V% > 50%)				
Latossolos	Oxisols	Ferralsols	6,280	0.12
Argissolos	Ultisols	Acrisols	202,510	4.10
Nitossolos	Alfisols	Nitosols	23,900	0.46
Plintossolos	Alfisols, Oxisols, Inceptisols	Luvisols Eutric, Nitosols	17,610	0.46
Cambissolos	Inceptisols	Cambislos	40,250	0.34
Gleissolos	Entisols e Inceptisols		270,400	0.78
Neossolos	Entisols	Gleysols	133,150	5.27
Others soils	-	-	28,380	2.59
Total			5,130,680	100.00

Sources: Fageria (1989); Rodrigues (1996).

ha, equivalent to 12.65% of the Brazilian Amazon (**Table 1**). Most of the deforested area is given over to pasture (degraded and non-degraded), with an estimated area of 52.5 million hectares, and to soybean growing, occupying around 5.7 million ha (responsible for 20% of national output). With soybean farming expanding at around 15% a year, it would take eight years for this crop to occupy the entire area of degraded pasture, without the need for new forest clearance.

ECOSYSTEMS

The soils in the Amazon are located basically in two ecosystems, floodplains and upland. As the name suggests, the floodplains are subject to periodic inundation by muddy rivers overflowing their banks (Solimões, Amazon and Madeira rivers, among others). They cover roughly 6.0 million hectares, with high potential for growing food crops. Although the soils are heterogeneous, because they were formed by deposition of sediments with different granulometric, mineralogical and organic compositions, they are generally rich in minerals, coming from the limestone formations of the Andes Mountains (**Table 2**).

Within the floodplain system there are two divisions according to the elevation in relation to the riverbed: high floodplains and low floodplains (Gleysols - FAO). The high floodplains, which receive the larger sediments in suspension in the water, have better drainage and are inundated for shorter periods, are more extensively cultivated. The low floodplains are further subdivided into two parts, those closer and farther from the river banks. The more distant areas are less fertile because at the start of the flood stage they are covered by waters from the swampy areas nearer the rivers, characterized by sediments poor in nutrients. The areas nearer the rivers have high fertility, but are only suitable for

short-cycle crops because they are under water for longer periods (Cravo *et al.* 2002).

It should be stressed that the soils along the black water rivers (e.g., Negro, Urubu and Japurá) or clear water ones (e.g., Tapajós) have low natural fertility because the waters from these rivers are poor in sediments and acidic. There are occasional exceptions, however, due to invasion of waters from larger muddy rivers during big floods.

In the Amazon, the upland takes in a wide variety of soils (Rodrigues 1986; Fageria 1989). As the name suggests, this land is not subject to the periodic flooding of the lower-lying regions. In these areas, normally, the acidic soils and high Al (Ferralsols and Acrisols – 75% of area) are the most common restrictions on fertility (**Table 3**).

Although the great majority of the soils in this ecosystem have low fertility, there are spots of reddish purple soil (Luvisols and Nitisols) that are highly fertile (Pandolfo, 1979). While small in terms of the entire Amazon, these soils are still quite abundant in absolute terms (**Table 4**).

SOILS

The region has great geological diversity, with the presence of sedimentary, metamorphic and magmatic rocks of distinct ages and origins (Malavolta 1987). A great part is covered by sediments from the Cretaceous-Quaternary period, of diverse natures, distributed in the east-west direction of the Amazon, covering the Acre Basin – Solimões Formation (Tertiary); Upper Amazon sub-basin – Ica Formation (Quaternary) and Middle and Lower Amazon sub-basins – Alter do Chão Formation (Cretaceous). On both sides of the great Amazon Valley (Solimões), there are Mesozoic sediments, which can be slightly diabasic. Among the main soil classes found in the Legal Amazon (**Table 2**), Ferralsols (Oxisols - Latossolos) and Acrisols (Ultisols - Argissolos) represent

Table 4 Areas with Luvisols (Alfisols) and Nitisols (Alfisols) in Brazilian Amazon.

Regions and States	Hectares	%
South of Pará State	750,000	69.44
Altamira (Pará State)	85,000	7.87
Alenquer, Monte Alegre and Fordlândia (Pará State)	65,000	6.02
Almeirim - Rio Jarí (Amapá State)	40,000	3.70
Rondônia State	70,000	6.49
Araguaína (Tocantis State)	20,000	1.85
Boca do Acre (Amazonas State)	20,000	1.85
Apui (Amazonas State)	20,000	1.85
Acre State	10,000	0.93
Total	1,080,000	100.00

Source: Pandolfo (1979).

Table 5 Characterization of soil fertility in Brazilian Amazon.

Soil chemical property	At adequate level	Below adequate (%)
pH (H$_2$O)	6.0	75 - 80
C (g kg^{-1})[1]	15.0	15 - 20
P (mg kg^{-1})[2]	8.0	85 - 90
K (cmol$_c$ kg^{-1})[2]	0.3	80 - 85
Ca (cmol$_c$ kg^{-1})[3]	4.0	75 - 80
Mg (cmol$_c$ kg^{-1})[3]	3.0	70 - 75
Al (cmol$_c$ kg^{-1})[3,4]	< 0.5	75 - 85
CTC (cmol$_c$ kg^{-1})	10.0	70 - 75
V% (base saturation)	60.0	80 - 85

[1] Walkley Black method; [2] Mehlich 1 extractant; [3] KCl 1.0 mol L^{-1} extractant; [4] Percentage above adequate.
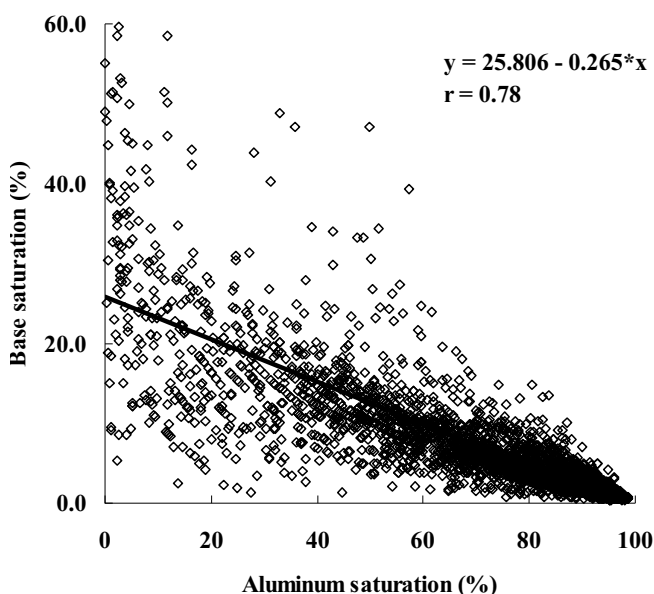Source: Malavolta (1987).

roughly 75% of the region's soils (Vieira and Santos 1987; Rodrigues 1996).

Soil fertility

Chemically, the soils are dystrophic [base saturation (ΣK,Ca,Mg/cation exchange capacity) < 50%] or alic [aluminum saturation ((Al/ΣK,Ca,Mg,Al)*100) > 50%], with the sum of the Ca and Mg content lower than 1.5 cmol$_c$ kg^{-1} and the base saturation less than 50% (Moreira and Malavolta 2002). In edafoclimatic conditions, the relationship between base saturation and aluminum saturation is inverse (**Fig. 1**). The contents of the bases (K, Ca and Mg exchangeable) and P available are also below the critical values used in interpretation of soil fertility. Together with the high Al content, these represent the greatest impediments to root development, negatively affecting plant growth (Malavolta 1987; Demattê 1988).

Despite the existence of large potentially tillable areas, the results of studies indicate that low soil fertility is the biggest limiting factor to agriculture in the region. The presence of an exuberant forest like the Amazon is explained mainly by the cycling of nutrients that occurs with the decomposition of organic matter along with the small loss by lixiviation, which together permit nutritional balance in soils with low natural fertility (Demattê 1988).

Accepting some values as adequate, Malavolta (1987) prepared a first broad approximation of the fertility of the Amazon soils (**Table 5**). The results show the presence of a high percentage of soils with high organic matter content, which can be a reflection of the intense primary production of plant residues and the large accumulation of litter. Although the region's high temperature and humidity favor decomposition, this accumulation probably is possible due to the low pH of the soils, which slows the decomposition and mineralization, permitting a balanced situation.

With relation to micronutrients, it is assumed that the high soil acidity that prevails in the region can favor increased availability of Cu, Fe, Mn and Zn (Havlin et al. 1999; Fageria and Stone 2008). However, this increase can be affected by the high rainfall in the region, which favors lixiviation, such as of the available Cu, present in the soluble chelates formed with the organic matter (SOM), which is easily washed away (Malavolta 1987). Regarding the Mn, the high SOM content of the region's soils can result in complexation of the element, reducing its availability to plants. The lack of Fe in most of the soils, despite the high total content of oxides, can be mainly caused by the oxidation process (Havlin et al. 1999; Fageria 2009).

In the Amazon, 23% of the soils are deficient in Cu and 48% in Zn (Nicholaides et al. 1983). These results and the low Fe availability in the soil are corroborated by Moreira et al. (2004) in an exploratory study of the nutritional state of banana plants grown in six municipalities in the Amazonas State, who observed that 50, 86.5, 62.1 and 96.4% of the plants showed deficiencies of Cu, Fe, Mn, and Zn, respectively. Rodrigues (1998), in a study of the availability of B, Cu, Fe, Mn, Mo and Zn with different extractors in five representative Amazon soils [Xanthic Ferralsol, "Indian Black Earth" (anthrosols – Xanthic Ferralsol), Gleysol, Acrisol Dystric and Podzol), found a significant variation in the contents, in function of the extractants and the soils studied (**Table 6**).

The content of available B in the Xanthic Ferralsol and Acrisol Dystric is in the range usually considered high (>0.5 mg kg^{-1} – Ribeiro et al. 1999). The lixiviation of this nutrient is possible impeded by the fixation of the B to the sesquioxides. On the other hand, the reservoir of available B is probably maintained by the combined action of the mineralization of the organic matter (a natural source of B) and the recycling. In the region's other representative soils the content is below that considered adequate (<0.3 mg kg^{-1} – hot water). The levels of available Cu and Zn, even in soil with high acidity that favors availability, which is the case of most soils of the region regardless of the extractor, are low on average, below levels considered adequate.

The content of available Mo in the region's soils varies from 0.21 to 0.41 mg kg^{-1} (Rodrigues 1998), but the low pH normally found, combined with the high level of sesquioxides and low available P can lead to deficiency of this nutrient in the plants (Havlin et al. 1999; Fageria and Stone 2008). There are no other reports analyzing this nutrient in the Amazon soils.

Mention should also be made of the anthropogenic soils (anthrosols), popularly called "Terra Preta de Índio" (Indian Black Earth or Amazonian Dark Earth), a name given the soils of anthropogenic origin in the Amazon (Woods 2003). These soils are generally found in circumscribed distribution near the rivers and are moistly distributed in areas covering from 2 to 5 ha (Teixeira and Martins 2002). They

$$y = 25.806 - 0.265*x$$
$$r = 0.78$$

Fig. 1 Relationship between base saturation and aluminum saturation at 0-20 cm soil depth (Moreira and Malavolta 2002).

Table 6 Concentration of micronutrients in five representative Amazon soils.

Elements	Extractants	Soils				
		Xanthic Ferralsol	Indian Black Earth [1]	Gleysol	Podzol	Acrisol Dystric
B (mg kg^{-1})	Mehlich 1	0.30	0.12	0.28	0.02	0.21
	Hot water	0.58	0.25	0.21	0.21	0.79
Cu (mg kg^{-1})	Mehlich 1	0.21	0.26	3.89	0.07	0.16
	DTPA-TEA	0.17	0.99	4.46	0.09	0.14
Fe (mg kg^{-1})	Mehlich 1	481.68	11.59	629.03	55.20	376.13
	DTPA-TEA	193.15	50.40	636.00	19.25	334.05
Mn (mg kg^{-1})	Mehlich 1	3.43	233.88	244.60	0.79	1.76
	DTPA-TEA	1.52	119.60	147.20	0.32	0.99
Mo (mg kg^{-1})	AB-DTPA	0.41	0.25	0.49	0.21	0.38
Zn (mg kg^{-1})	Mehlich 1	0.76	4.92	8.86	0.42	0.65
	DTPA-TEA	0.26	1.78	7.20	0.15	0.25

[1] anthrosols - Xanthic Ferralsol.
Source: Rodrigues (1998).

Table 7 Soil fertility of Indian Black Earth, soil depth 0-20 cm[1].

Municipalities	pH				K	Ca	Mg	Al
	H$_2$O	M1	M3	Bray 1	M1	KCl		
			--------- mg kg^{-1} -----------			------ cmol$_c$ kg^{-1} -------		
Iranduba (AM)	4.11	292	231	264	12	2.7	1.3	0.11
Iranduba (AM)	4.23	1093	475	318	26	3.5	5.4	0.11
Iranduba (AM)	5.03	86	97	45	16	1.3	0.2	0.21
Manacapuru (AM)	4.76	549	471	556	183	10.9	4.1	0.03
Manacapuru (AM)	5.72	339	274	334	38	9.1	1.1	0.11
Barreirinha (AM)	5.70	244	-	-	137	10.2	2.7	0.01
Rio Preto da Eva (AM)	4.11	117	110	87	12	2.7	1.3	0.11
Rio Preto da Eva (AM)	4.28	254	186	220	26	3.5	5.4	0.11
Rio Preto da Eva (AM)	4.36	269	178	183	40	9.5	6.3	0.12
Parintins (AM)	4.66	936	491	816	38	24.6	5.6	0.11
Santarém (PA)	4.84	292	231	264	38	31.4	3.2	0.08
Oriximiná (PA)	4.85	272	-	-	44	13.8	4.0	1.10
Portel (PA)	-	1001	-	-	24	9.3	2.8	1.8

M1 - Mehlich 1 extractant; M3 - Mehlich 3 extractant; KCl - KCl 1.0 mol L^{-1}. AM - Amazonas State; PA - Pará State.
Source: Moreira (2007).

have high nutrient contents, mainly Ca and P, high organic matter levels (Kern and Kämpf 1989; Kern and Costa 1997; Moreira 2007) and high biological activity in comparison with the adjacent soils, the majority of which are kaolinitic and strongly weathered (**Table 7**).

The "Indian Black Earth" is characterized by a dark-colored anthropic A horizon over Ferralsols, Acrisols and Cambisols. Many aspects of the origin or this soil are not yet clear, but it was probably formed by pre-Columbian peoples and then abandoned after the European invasion (Kern and Kämpf 1989). Nevertheless, many doubts remain, among them the high capacity to remain fertile under continuous use even under the local edaphoclimatic conditions.

Nutrient cycling in unaltered and altered systems

Because the soils are for the most part poor, the region's forests are normally in dynamic equilibrium (**Fig. 2**). The cycling of nutrients is the most important process for this balance. With anthropic activities, mainly consisting of deforestation, removal of valuable wood, subsequent use of burned areas to grow annual or perennial crops or to form pasture, this process is severely affected (Andreux and Cerri 1989). Various studies report changes in the soil C and N content, increased pH and content of exchangeable cations (K, Ca, Mg and Na) and reduction of exchangeable acidity (H+Al) resulting from cutting and burning the natural forest (Martins *et al*. 1991).

The removal of the forest reduces the activity of the microbial biomass, the main factor responsible for introducing nutrients into the system and for the flow of energy within the soil (Andreux and Cerri 1989; Dalal 1998). Measurements of the microbial biomass have been used in studies of C and N, nutrient cycling and plant yield in different land ecosystems. These measurements permit quantifying the living biomass present in the soil at a particular time. They also enable associating the quantity of immobilized

nutrients and the microbial biomass activity with the fertility and potential soil productivity, serving as a base for studies of the formation and cycling of organic matter. Since the microbial biomass is the largest active fraction of organic matter, it is thus a more sensitive indicator than organic C and total N to ascertain changes in the levels of organic matter in the soil caused by cultivation and other human uses (Paul and Clark 1989).

One study of reforestation of cleared areas with native plants found that even 10 years after replanting, the stock of carbon in the soil was 60% less than in primary forest soil, while the C of the microbial biomass was 67% less (Moreira and Costa 2004). With primary forest succession and planting of cupuassu (*Theobroma grandiflorum*) for three years and primary forest succession and planting of cupuassu for three years, planted in a former pasture area of *Brachiaria humidicola* (tropical pasture), maintained for eight years, the C of the microbial biomass declined 33.3 and 24.4%, respectively (Moreira and Malavolta 2004).

In this equilibrium, the deposition of organic matter in the Amazon soils (the greatest source of nutrients) varies according to the type of vegetation, and is directly related to the content deposited, coming from the dry weight and roots. In the humid tropical part of the Brazilian Amazon (Acre, Amazonas, Pará, Rondônia and Amapá States), the forest soils receive high quantities of leaves, stems, etc., considerably increasing the surface layer. This does not occur in the region's savanna areas (part of Roraima, Mato Grosso, Tocantins and Maranhão States). These areas are mainly covered with grasses, bushes and small trees and the surface accumulation of organic matter is strongly influenced by the climate conditions, with prolonged dry periods, and by the type of dominant plant cover.

Organic matter levels higher than in the primary forest soils were found under stands of 17-year-old rubber trees. In samples taken at varying depths the respective OM contents were: 0 to 10 cm – 38.1 g kg^{-1}; 10 to 20 cm – 29.4 g
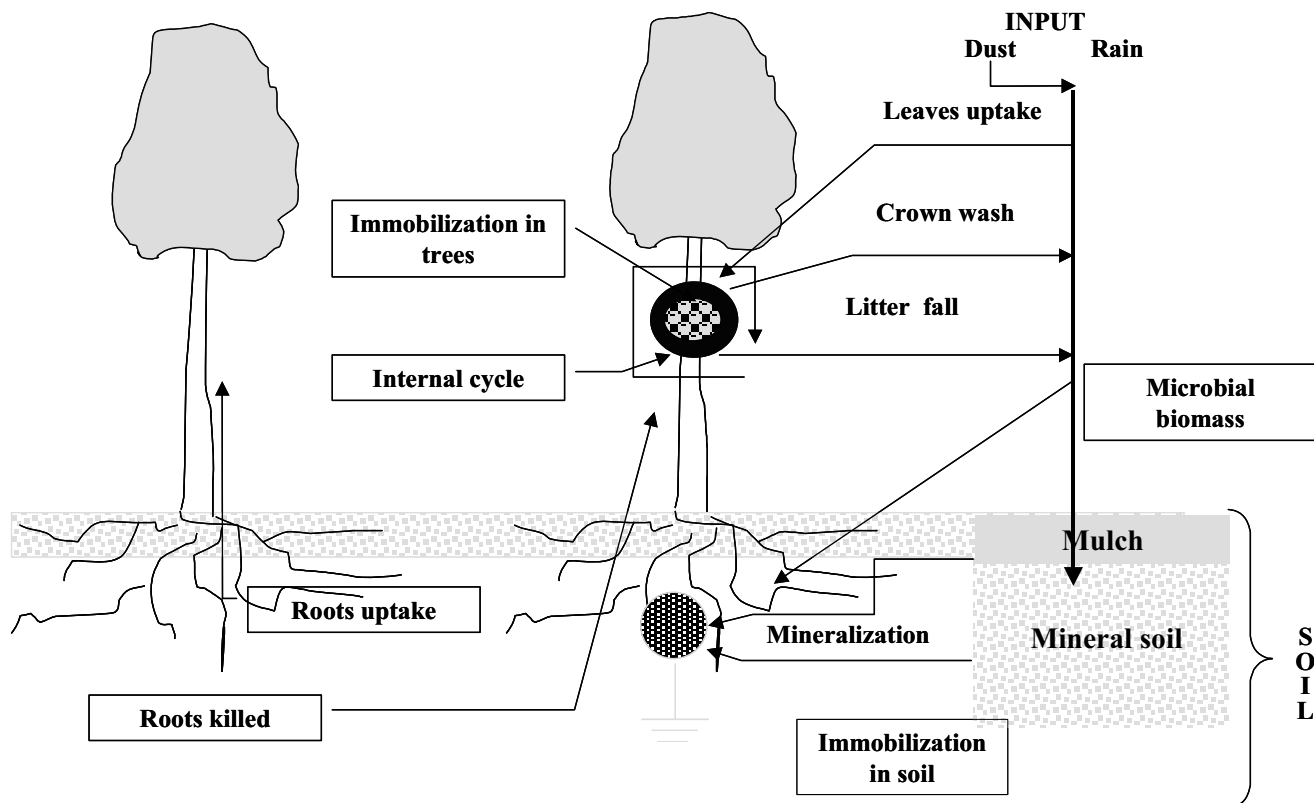
Fig. 2 Dynamic of nutrients in natural ecosystem of Amazon (Modified from Miller 1984).

kg^{-1}; 20 to 40 cm – 17.4 g kg^{-1}; and 40 to 60 cm – 12.6 g kg^{-1}. These values were equivalent to a stock of approximately 23 metric tons of C per ha (Moraes and Moreira 2003). Agroforestry is another alternative to restore the soil's organic matter, mainly in systems that use leguminous plants (*Erythrina mulungu*, *Inga edulis* and *Cajanus cajan*), which accumulate nutrients while growing, principally N. When these plants are pruned and the trimmings are used as mulch, a large part of the nutrients are returned to the soil in a form more easily assimilated by the plants.

In the Amazon, the organic matter is basically formed from the decomposition of plant wastes of the same composition as the surrounding plants. However, due to climatic and pedological diversity, there are differences in the quantity, since the climate can interfere in the humification processes and rate of carbon renovation in the soil. The stock of carbon in different places (Pará, Rondônia and Amazonas States) varies little, with the average value being 1.98 ± 0.31 kg m^{-2} (Cerri *et al*. 1996). Because of the system's fragility, deforestation and consequent removal of plant cover for agriculture can cause a breakdown in the carbon and nutrient cycles in the soil.

The evaluation of the losses of organic matter and nutrients from the forest with the introduction of agriculture and other soil management practices is important, because these human activities significantly interfere in the cycling of nutrients, which affects the fertility longevity of the soil. More detailed studies of the organic matter dynamic are necessary to gain a better understanding of this ecosystem.

Use of fertilizers and correctives

Despite the great agricultural potential of some parts of the Legal Amazon, there are still relatively few studies on the soil fertility, especially on the adequate use of fertilizers and soil correctives. In the region many recommendations are based on findings from areas with different edaphoclimatic characteristics. This can lead to underestimating the dose of the one nutrient in a particular crop.

Efficient use of fertilizers and correctives require methods of diagnosis and recommendation that can predict the suitable quantities of lime and fertilizers for crops of interest in the region. For efficient use of recommendations it is necessary to consider the following factors (Smyth 1996): a) existing content of the nutrient in the soil; b) the adequate level of element in the soil for the particular target crop; c) the existing element content in the leaves diagnosed; d) the adequate element level for the target crop; and e) the fertilizers and correctives rates that need to be applied to raise the element level in the soil and the plant to the level considered adequate. Due to the high price of agricultural inputs in the region, the cost-benefit ratio must be considered to obtain maximum profitability.

Regional calibration tests are important for a suitable recommendation. One of the few examples is phosphate fertilization of corn. In the savanna regions, the recommendation is 79 kg ha^{-1} of P to reach the critical level of 10 mg dm^{-3} (Goedert *et al*. 1986), while in the forest area, more specifically, in dystrophic yellow Latosol (Xanthic Ferralsol) in the Manaus region, application of 94 kg ha^{-1} of P$_2$O$_5$ is to reach a critical level of 6 mg dm^{-3} (Smyth and Cravo 1990). The maximum yields of corn and greater capacity for sorption of P in the Latosols (Oxisols) of the savanna regions are probable factors that contribute to this difference (Smyth 1996).
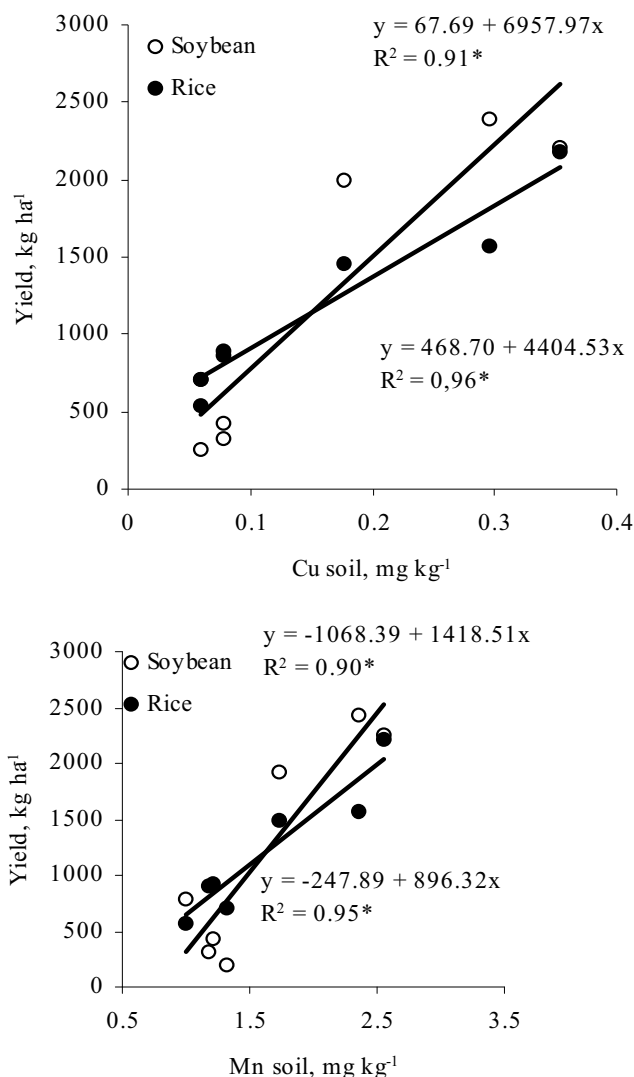
All the same, the Mato Grosso, Pará and Rondônia States are where the greatest soybean yields in the country have been obtained, with average productivity of 2.8, 2.8 and 2.9 metric tons per hectare, respectively, higher figures than in other Brazilian states, such as Rio Grande do Sul (2.7 t ha^{-1}) and Paraná States (2.5 t ha^{-1}), and countries, such as the United States (2.4 t ha^{-1}), Argentina (2.4 t ha^{-1}), China (1.7 t ha^{-1}) and Paraguay (2.4 t ha^{-1}). The average soybean yield in states lying within the Legal Amazon average above 2.2 t ha^{-1} (**Table 8**).

In a three-year study in the central Amazon (Amazonas State) of the residual effect of liming and micronutrients in Xanthic Ferralsol, Alfaia and Muraoka (1997) found that the application of lime (2, 3 and 5 t ha^{-1}) together with micronutrients (5 kg ha^{-1} of Cu; 7.5 kg ha^{-1} of Mn; 0.5 kg ha^{-1} of Mo; 4.5 kg ha^{-1} of Zn; 2.0 kg ha^{-1} of B) caused significant increases in rice and soybean yields. In this period,

Table 8 Soybeans yield, area and productivity in the Brazilian Amazon (2007).

States - Brazil	Yield (metric ton)	Area (ha)	Productivity (kg ha^{-1})
Acre	300	100	3.0
Amapá	-	-	-
Amazonas	1,931	806	2.4
Mato Grosso[1]	7,637,444	2,537,539	3.0
Maranhão[1]	843,821	269,132	3.1
Pará	154,015	53,553	2.9
Rondônia	259,069	89,520	2.9
Roraima	20,300	7,000	2.9
Tocantins	731,672	304,096	2.4
Average	1,206,069	369,706	2.8

Sources: Embrapa (2004); IBGE (2008).
[1] Yield only of Brazilian Amazon

$$y = 67.69 + 6957.97x \quad R^2 = 0.91*$$

$$y = 468.70 + 4404.53x \quad R^2 = 0,96*$$

$$y = -1068.39 + 1418.51x \quad R^2 = 0.90*$$

$$y = -247.89 + 896.32x \quad R^2 = 0.95*$$

Fig. 3 Relationship between soybean and rice yield with available Cu and Mn – Mehlich 1 extractant (Alfaia and Muraoka 1997).

the outputs were highly correlated with the levels of available Cu and Mn (Mehlich 1 extractant) in the soil (**Fig. 3**), but the same did not occur with the other micronutrients analyzed (Zn and Fe – Mehlich 1 extractant). The highest estimated rice yield obtained (2,133 kg ha^{-1}) was slightly below that of the northern region, the place where the traditional rice-growing states are located, such as Roraima and Tocantins States. The highest estimated soybean yield was 2,357 kg ha^{-1}, a value higher than productivity of the Amazonas State but below that obtained in the northern region (**Table 7**).

In a Xanthic Ferralsol in the municipality of Capitão Poço (Pará State), output of orange trees fertilized with NPK was 58 t ha^{-1}, with application of 300 g plant^{-1} of N,

230 g plant^{-1} of P_2O_5 and 75 g plant^{-1} of K_2O (Veloso *et al.* 2003). Other positive results have been obtained in the region with the use of agricultural inputs, particularly sulfur. In the savanna biome, Sfredo *et al.* (2003) obtained average soybean yield of 3120 kg ha^{-1} with a dose of 50 kg ha^{-1} of S in the municipalities of Sambaíba (Maranhão State) and Rondonópolis (Mato Grosso State).

CONCLUSIONS

The Brazilian Amazon region has extensive areas of savanna (Mato Grosso, Tocantins, Roraima, Rondônia and Pará States) and eutrophic soils, along with 6.0 million ha of floodplains. Currently the highest grain yields are being obtained in areas at the margins of the region, mainly in savanna areas. In deforested areas, the pasture and soybean, the fastest-expanding crop in the region, is responsible for 20% of Brazilian output of grain, occupying roughly 5.7 million ha. Even with this high potential, the soils are for the most part characterized by high acidity and low availability of nutrients (0.4 billion ha – 86% of the area), with the primary forest dependent on decomposition of organic matter and recycling of nutrients. Under the distinct climate conditions of the humid tropical part, with extensive rainy periods and river flooding, restricting cultivation of annual crops (such as rice) produces reasonable yields. In the more elevated terra firma areas, with propitious climate conditions, the planting of exotic and native tropical fruit species in combination or monoculture has great potential. However, high investments are necessary in research and infrastructure for soil conservation and adequate use of fertilizers and soil correctives.

REFERENCES

Alfaia SS, Falcão NP (1993) Study of nutrients dynamics in floodplain soils of the Careiro island. *Amazoniana* **12**, 485-493

Alfaia SS, Muraoka T (1997) Residual effect of lime and micronutrients on an Oxisol under crop rotation. *Acta Amazonica* **27**, 153-162

Andreux F, Cerri CC (1989) Current trends in the research on soil changes due to deforestation, burning and cultivation in the Brazilian tropics. *Toxicological Environmental Chemistry* **20/22**, 275-283

Becker BK (2001) Revisão das políticas de ocupação da Amazônia: é possível identificar o modelo para projetar cenários? *Parcerias Estratégicas* **12**, 135-159

Cerri CC, Bernoux M, Volkoff B, Moraes JL (1996) Dinâmica do carbono nos solos da Amazônia. In: Alvarez Venegas VH, Fontes LEF, Fontes MPF (Eds) *O Solo nos Grandes Domínios Morfoclimáticos do Brasil e o Desenvolvimento Sustentado*, Viçosa, SBCS, pp 61-69

Cravo MS, Xavier JJBN, Dias MC, Barreto JF (2002) Characteristics, potential and actual agricultural use of floodplain in the Amazonas States, Brazil. *Acta Amazonica* **32**, 51-365

Dalal RC (1998) Soil microbial biomass – what do the number really mean? *Australian Journal of Experimental Agriculture* **38**, 649-665

Demattê JLI (1988) *Manejos de Solos Ácidos dos Trópicos Úmidos – Região Amazônica*. Campinas, Fundação Cargill, 215 pp

Embrapa (1984a) *Levantamento de Reconhecimento de Média Intensidade dos Solos e Avaliação da Aptidão das Terras da Área do Pólo Trombetas*, PA. Rio de Janeiro, Embrapa solos, 440 pp

Embrapa (1984b) *Relatório Técnico Anual da Unidade de Execução de Pesquisa de Âmbito Estadual de Manaus – 1982/1983*, Embrapa UEPAE de Manaus, Manaus, 360 pp

Embrapa (2004) *Reunião de Pesquisa de Soja da Região Central do Brasil*, Embrapa Soja, Fundação Meridional, Londrina, 272 pp

Fageria NK (1989) *Solos Tropicais e Aspectos Fisiológicos das Culturas*, Brasília, Embrapa, 423 pp

Fageria NK (2009) *The Uses of Nutrients in Crops Plants*, CRC Press, Boca Raton, 430 pp

Fageria NK, Stone LF (2008) Micronutrients deficiency problems in South America. In: Alloway BJ (Ed) *Micronutrients Deficiencies in Global Crop Production*, Springer, London, pp 245-266

Goedert WJ, Sousa DM, Lobato E (1986) Fósforo. In: Goedert WJ (Ed) *Solos dos Cerrados; Tecnologia e Estratégias de Manejo*, Nobel, São Paulo, pp 129-166

Havlin J, Beaton JD, Tisdale SL, Nelson WL (1999) *Soil Fertility and Fertilizers; An Introduction to Nutrient Management*, Prentice Hall, Upper Saddle River, 499 pp

IBGE (2000) Instituto Brasileiro de Geografia e Estatística. Rio de Janeiro, IBGE. Available online: http: www.ibge.gov.br

IBGE (2008) Instituto Brasileiro de Geografia e Estatística - SIDRA. Rio de

Janeiro, IBGE. Available online: http: www.ibge.gov.br

Kern DC, Costa ML (1997) Composição química de solos antropogênicos desenvolvidos em Latossolo Amarelo derivados de lateritos. *Geociências* **16**, 141-156

Kern DC, Kämpf N (1989) Antigos assentamentos indígenas na formação de solos com terra preta arqueológica na região de Oriximiná, Pará. *Revista Brasileira de Ciência do Solo* **13**, 219-225

Malavolta E (1987) Fertility of Amazon soils. In: Vieira LS, Santos PCTC (Eds) *Amazon, its Use and Other Natural Resources*, São Paulo, Agronômica Ceres, pp 374-416

Martins PFS, Cerri CC, Volkoff B, Andreux F, Chauvel A (1991) Consequences of clearing and tillage on the soil of a natural Amazonian Ecosystem. *Forest Ecology and Management* **38**, 173-182

Miller HG (1984) Nutrient cycles in birchwoods. *Proceeding of the Royal Society of Edinburgh* **853**, 83-96

Moraes VHF, Moreira A (2003) *Potencial de Contribuição da Cultura da Seringueira para Conservação do Ambiente no Trópico Úmido*, Embrapa Amazônia Ocidental, Manaus, 18 pp

Moreira A (2007) Soil fertility, organic matter and humic compounds in anthropogenic soil of Western Amazon. *Bragantia* **66**, 307-315

Moreira A, Costa DG (2004) Organic matter dynamics in the recovery of clearing of the Amazon Forest, Brazil. *Pesquisa Agropecuária Brasileira* **39**, 1013-1020

Moreira A, Malavolta E (2002) Variação das propriedades químicas e físicas do solo e na matéria orgânica em agroecossistema da Amazônia Ocidental (Amazonas), CENA/USP, Piracicaba, 79 pp

Moreira A, Malavolta E (2004) Dynamic of organic matter and microbial biomass in a soil under different management systems in the Western Amazon. *Pesquisa Agropecuária Brasileira* **39**, 1103-1100

Moreira A, Pereira JCR, Arruda MR (2005) Nutritional diagnosis of banana plantations in the State of Amazonas, Brazil. *Revista de Ciências Agrárias* **43**, 29-42

Nicholaides JJ, Sanchez PA, Bandy DE, Villachica JH, Coutu AJ, Valverde CS (1983) Crop production systems in the Amazon Basin. In: Moran EF (Ed) *The Dilemma of Amazonian Development*, Westview Press, Boulder, pp 101-154

Pandolfo C (1979) *Brazilian Amazon and its Potentiality*, SUDAM, Belém, 74 pp

Paul EA, Clark FE (1989) *Soil Microbiology and Biochemistry*, Academic Press, California, 275 pp

Ribeiro AC, Guimarães PTG, Alvarez Venegas VH (1999) *Recommendations for Use of Amendments and Fertilizers in Minas Gerais, 5th Approximation*, SFSEMG, Viçosa, 359 pp

Rodrigues MRL (1998) Disponibilidade de micronutrientes em solos da Amazônia. PhD thesis – Escola Superior de Agricultura "Luiz de Queiroz", Universidade de São Paulo, Piracicaba, 156 pp

Rodrigues TE (1996) Solos da Amazônia. In: Alvarez Venegas VH, Fontes LEF, Fontes MPF (Eds) *O Solo nos Grandes Domínios Morfoclimáticos do Brasil e o Desenvolvimento Sustentado*, SBCS, Viçosa, pp 19-60

Sá TDA (2005) Processos de degradação e recursos naturais na Amazônia Brasileira; prioridade para intervenção. In: *Simpósio sobre Sistemas Agroflorestais*, Embrapa Amazônia Oriental, Belém, pp 1-30

Salati E, Ribeiro MNG, Absy ML, Nelson BW (1991) Clima na Amazônia: presente, passado e futuro. In: Val AL, Figliuolo R, Feldberg E (Eds) *Base Científica para Estratégias de Preservação e Desenvolvimento da Amazônia: Fatos e Perspectivas*, INPA, Manaus, pp 21-34

Sfredo GJ, Klepker D, Sibaldelli R, Morais JS (2003) Resposta da soja à aplicação de enxofre em quatro localidades do Brasil. In: *Reunião de Pesquisa de Soja da Região Central do Brasil*, Embrapa Soja, EPAMIG, Fundação Triangulo, Londrina, pp 135-136

Smyth TJ (1996) Manejo da fertilidade do solo para produção sustentada de cultivos na Amazônia. In: Alvarez Venegas VH, Fontes LEF, Fontes MPF (Eds) *O Solo nos Grandes Domínios Morfoclimáticos do Brasil e o Desenvolvimento Sustentado*, SBCS, Viçosa, pp 71-93

Smyth TJ, Cravo MS (1990) Critical phosphorus level for corn and cowpea in a Brazilian Amazon Oxisol. *Agronomy Journal* **82**, 309-312

Teixeira WG, Martins GC (2003) Soil physical characterization. In: Lehmann J, Kern DC, Glaser B, Woods WI (Eds) *Amazonian Dark Earths; Origin, Properties and Management*, Kluwer Academic Publishers, Dordrecht, pp 271-286

Veloso CAC, Muniz ACM, Pereira WLM, Souza FRS, Carvalho EJM (2003) Rendimento e qualidade de frutos da laranjeira submetida à adubação com NPK em Latossolo Amarelo. *Revista de Ciências Agrárias* **40**, 133-144

Vieira LS, Santos PCTC (1987) *Amazon, its Use and Other Natural Resources*, Agronômica Ceres, São Paulo, 416 pp

Woods WI (2003) Development of antrosol research. In: Lehmann J, Kern DC, Glaser B, Woods WI (Eds) *Amazonian Dark Earths; Origin, Properties and Management*, Kluwer Academic Publishers, Dordrecht, pp 3-14