Soil Alterations in Perennial Pasture and Agroforestry Systems in the Brazilian Amazon

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I. Introduction

The Brazilian Amazon has been, in the past two decades, particularly, in the past decade, the center of world attention due to present and potential ecological implications of man's utilization of natural resources for development purposes. In this context, agricultural development has been the most important factor of environmental disturbances in the past three decades. At least 40 million hectares of forest land (an area corresponding to the size of eight Costa Ricas) have been altered for development of land use systems that, in general, have shown low levels of sustainability from a biophysical (agrotechnical and environmental) and socioeconomic point of view.

The search for sustainable agricultural and forestry development in the Amazon is a great challenge for farmers and governmental and non-governmental institutions involved in the process. Within this context, sustainable manage-

ISBN 1-56670-076-0

ment of soil resources in the Amazon is a very important issue for agronomic, ecologic and socioeconomic considerations.

This paper presents research information on productivity and physical and chemical soil alterations in land use systems with present and potential importance for sustainable land development in the Amazon.

II. The Basis for Agricultural Sustainability in the Amazon

Any proposal for agricultural and forestry development in the Amazon must take into account the need to promote sustainable land use systems. The possibility of developing a sustainable land use system in the region depends on its permanence in an area and on increasing land and labor productivity standards, thereby reducing the pressure for more deforestation. This concept of sustainability necessarily implies an equilibrium in time among agrotechnical, economic, ecological and social feasibility. This equilibrium is frequently fragile in Amazonian agricultural systems and no agricultural land use system in this region meets all these pre-requisites of sustainability at highly satisfactory levels (Serrão and Homma 1993).

III. Land Use Systems and Their Present Sustainability in the Amazon

Serrão and Homma (1993) made an analysis of the sustainability (as defined above) of selected land use systems because of their present and potential importance due to scale of utilization, types of farmers involved, economic importance, possibilities for future markets, environmental implications, and technological and productivity patterns. In general, these authors suggest that agrotechnical, environmental, and socioeconomic sustainability equilibrium is low for most land use systems and that it is lower for those systems that involve forest conversion at varying levels (mainly ranching, shifting agriculture, upland perennial and semi-perennial crop production, and timber extraction) as compared to those developed on non-forest ecosystems (crop and cattle production on *varzea* floodplains and well- and poorly-drained savannas).

Of major importance, due to their environmental and socioeconomic implications, are those land use systems that demand deforestation for their development. In the frontier opening process in the region, and due to prevailing socioeconomic environment, these land use systems have involved large-scale slash-and-burn activities. Typically, land use intensity decreases from road side areas to areas further into the forest. Negative environmental implications (in terms of carbon emission and loss of biodiversity, biomass, soil, water, nutrients and fire resistence) increase with extensive agriculture activities.

IV. The Need to Increase Sustainability of Agricultural Activities on Already Altered/Deforested Lands

More than enough land has already been deforested for unsustainable agricultural development in the Amazon. From an agrotechnical point of view, it is possible to produce sufficient amounts of food and fiber to meet the demand of the region's population for the next couple of decades by properly utilizing (increasing sustainability) already altered/deforested lands with no further need to use primary forests, except for selective timber extraction and extraction of non-timber products.

On those lands, agricultural land use systems must have higher levels of sustainability than the unsustainable systems that have been practiced, especially in the past 30 years. Alternative sustainable agricultural land use systems will require efficiency of resources (soil nutrients, biomass, biodiversity, genetic resources, climate) whether they are monoculture, polyculture, or integrated systems.

V. The Importance of Soil Resource Management for Securing Agricultural Sustainability in Deforested Lands in the Amazon

Agrotechnical sustainability—the capacity of a land use system to maintain its productivity in the same area for as long a period of time as possible—depends on prevailing climatic, biotic (pests, deseases, weeds, etc.), and edaphic (chemical, physical, and biological) conditions. Climatic and biotic factors are of the utmost importance, but they are not within the scope of this paper.

Soil resource management is critical for agricultural development in deforested land in the Amazon. On the one hand, most of the area that has been deforested for agricultural development has soils that are acid and nutrient-deficient, although adequate from the point of view of their physical features. On the other hand, the socioeconomic environment in the region does not allow for intensive fertilizer and liming utilization in agriculture. Therefore, soil resources conservation, especially soil nutrient conservation, is essential for sustainable agricultural development from the point of view of agrotechnical and economic sustainability. For example, it has been estimated (Uhl et al., in press; Serrão, in press) that, in the process of deforestation for pasture formation and during the pasture-use period, a significant portion of the nutrients embodied in the slashed forest biomass is leached from the ecosystem. This loss is valued at close to US$3,500 per hectare, given current prices of NPK fertilizers in Brazil. This does not mean to suggest that this much fertilizer would be necessary to restore soil fertility in degraded pastures. Nor does it imply that these pastures are closed ecosystems in regard to nutrients. Clearly, nutrients enter those ecosystems via atmospheric deposition and weathering. The point is that measurable quantities of nutrients are lost in the conversion of forest to pasture, (there is a similar situation in shifting agriculture) and it is necessary to consider about how to estimate the cost of these losses and search for and develop alternative agricultural production systems that will minimize them and thus increase agrotechnical and economic sustainability with the consequent positive effect on social and ecological sustainability.

From the above considerations, it becomes clear that it is absolutely necessary to understand the soil processes and modifications which lead to soil improvement or degradation due to land utilization for agricultural and forestry development activities in the Amazon.

VI. Long-Term Soil Management Experiments in the Amazon

Very few research attempts have been made to evaluate chemical and physical soil modifications under agricultural and forestry activities in the Amazon. This is explained mainly due to the fact that the majority of the region's most important transformations in the agricultural production sector started in the 1960s, with an aggressive expansion of the agricultural frontier which has been characterized by accelerated large-scale and aggressive exploration of natural resources. This type of development began to raise concern within the local and foreign research community in searching for ways to evaluate soil-plant and soil-plant-animal relations in the region. The following are probably the few most relevant research attempts to evaluate physical and chemical soil modifications under prevailing land use systems in the Amazon. These research attempts have been made mainly in two types of land use systems which demand deforestation for their development: large-scale extensive pasture-based ranching and small-scale agroforestry systems.

A. Soil Transformation in Large-Scale Pasture Experiments Systems

It is estimated that at least 60% of the present total deforestation (around 40 million hectares) in the Amazon have been for cattle-raising activities, most of which has occurred in the last three decades.

For a better understanding of this segment, a few definitions and explanations are needed.

1. Definitions

lst-cycle pastures (or pioneer pastures): those formed from the moment the primary forest is cleared.

2nd-cycle pastures (or 2nd generation pastures): those resulting from the recuperation (or renovation) of degraded pioneer pastures.

Degraded pastures: those in which the biomass of the weed community predominates in relation to that of sown forage plants.

2. Explanations

Typically, lst-cycle pastures (presently still the majority of planted pastures in the region) have been formed by sowing soil nutrient-demanding pioneer grasses, such as "guineagrass" (*Panicum maximum*), which has been the most common species, after the clearing and burning of the forest. In general, during the first 3 or 4 years after establishment, productivity in these pioneer pastures is relatively high. However, after this period, there is a gradual (but fairly rapid) decline in the productivity of the planted grass, which is accompanied by an increasing presence of weeds, the pasture reaching advanced stages of degradation on the average after 5 to 7 years after establishment. This pasture-life period varies with prevailing environmental and management factors. More recently, productivity in lst-cycle pastures has improved with the planting of less soil-fertility-demanding grasses such as *Brachiaria humidicola, Andropogon gayanus* and *Brachiaria brizantha*.

When 1st-cycle pastures reach degradation, ranchers tend either to abandon degraded pastures to fallow for an intermediate period or re-establish new pasture systems—the 2nd-cycle pastures. Establishment of 2nd-cycle pastures involves more intensive technological practices, such as mechanization for land preparation and planting and fertilization (especially P fertilization, as will be seen later in this paper) for better pasture establishment. Details of pasture establishment, degradation, and reclamation in the Amazon can be found in Serrão et al. (1979), Serrão and Toledo (1982), Serrão and Toledo (1992), Serrão and Dias Filho (1991).

3. "Long-Term" Pasture Experiments

There are no long-term experiments (with at least 10-year duration) to evaluate soil changes under pasture in the Amazon. However, two relevant research attempts have been made with important information resulting from them. Two studies were carried out simultaneously in northern State of Mato Grosso and eastern State of Pará between 1968 and 1973 in extensive commercial 1st-cycle pastures of "guineagrass" (Falesi, 1976; Baena, 1978; Serrão et al., 1979). These studies had the objective of "accompanying" and comparing physical and chemical soil changes in pastures of different ages (years after slashing and burning of the forest biomass and sowing of guineagrass) with soil conditions in the adjacent unexploited primary forest. This was done by selecting two private ranches which had pastures with ages varying from 1 to 11 years (in northern Mato Grosso) and 1 to 10 years (in Eastern Pará) after establishment.

The eastern Pará site soil is an Oxisol (a medium-texture Yellow Latosol) area, originally covered by dense rain forest, the climate being a transition of Am to Aw climatic type of the Koppen climate classification.

The northern Mato Grosso site soil is also an Oxisol (a medium-texture Dark Yellow Latosol) area originally covered by open forest with the predominant climate being the Aw type of the Koppen classification. For each age, a representative average pasture (in terms of management history) was chosen to be sampled for determining the soil physical and chemical attributes from the soil surface to a 20-cm depth.

In this traditional process of pasture establishment and utilization in the region, after the clearing and burning of the forest, substantial amounts of nutrients are incorporated in the soil through ash deposition, significantly increasing soil fertility, raising pH in at least one unit and practically neutralizing soil Al. Most importantly, these results indicate that with time, in those soils under guineagrass pastures, nutrients such as Ca and Mg are maintained at fairly satisfactory levels, pH values are maintained between 5.5 and 6.5 and Al is kept practically neutralized. As a consequence, BS seldom is smaller than 50% and Al is pratically nil. K is maintained fairly stable at fairly satisfactory levels for maintaining pasture productivity. A similar trend can be observed for OM and N, in spite of periodic pasture burning, a typical 1st-cycle pasture management practice in the region.

Phosphorus, in its available form, increases considerably in the soil right after burning of the slashed forest to levels sufficient to propitiate fairly high pasture productivity during the first 4 to 5 years. After these first years, available soil P declines rapidly to levels which are incompatible with pasture growth as can frequently be seen in degraded commercial 10-year-old, 1st-cycle pastures.

Although inadequate grazing systems and grazing pressures undoubtedly contribute to a more or less rapid process of 1st-cycle pasture degradation in the region, these results indicate that P is the most limiting soil nutrient for maintaining pasture productivity in forest-replacing pastures in the Amazon. On the other hand, it has been observed by the authors of this paper that pasture productivity decline tends to be faster and more accentuated in soils with higher clay content, which is aggravated by low levels of soil P and high grazing pressures.

Although this experiment cannot be referred to as a true long-term soil resource management experiment and did not include measurement of pasture productivity, its results have become very valuable for a better understanding of the trends in soil nutrients under extensive pasture development in the region.

Following these findings, a series of small-plot and grazing experiments in the region have confirmed the importance of P as the main limiting nutrient for increasing pasture agrotechnical sustainability in the region (Serrão et al., 1979). In the last decade, at least 1.5 million hectares of degraded 1st-cycle pastures have been reclaimed into more sustainable 2nd-cycle pastures. In this process, P fertilization has been imperative. Abandoned degraded pastures seem to be able to conserve most of the other nutrients at relatively satisfactory levels, imitating, in some measure, the forest nutrient-conserving mechanisms which allow for satisfactory regeneration of a forest ecosystem which may be similar to the primary forest ecosystem (Bushbacher et al., 1988; Uhl et al., 1988).

A similar study was conducted, at the Distrito Agropecuário, on the Br-174 highway, about 50km east of Manaus, in Central Amazon (Teixeira, 1977; Teixeira & Bastos, 1989). In this region the area of forest transformed into pasture is small when compared with the areas in the State of Pará where the experiments described above were conducted.

In this case, the experimental area was of a typical primary forest ecosystem. The predominant soil in the region of Manaus is clayey Oxisol (Yellow Latosol), acidic and of low fertility. The climate is of the Am type in the Koppen classification system. In this experiment a forest area and five adjacent *Brachiaria humidicola* pastures, of one, two, six, seven, and eight years of age were studied.

The objective of the study was to identify the alterations in the soil in the pastures of different ages in relation to the soil of the primary forest. The pastures were established following the usual procedure of cutting (May 1977) and burning (October 1977) of the forest biomass and planting of *B. humidicola* (March 1978).

Table 1 shows the parameters of fertility of the soil under forest and pastures. The burning of the forest biomass, substantially increased, in the layer from 0-10cm, the total base and base saturation values. The soil pH also increased. On the other hand, the values for exchange capacity were not altered. The values of exchangeable aluminum diminished from levels considered toxic to less harmful levels, and the values for aluminum saturation had a very accentuated initial reduction, stabilizing in the soil under pasture at about 30%.

The increase in total base and base saturation, as well as in soil pH, occurred due to the increase in exchange bases in the soil. The cation exchange capacity (CEC) value found in the soil under pasture is similar to that determined for the soil under forest. According to Bittencourt (1977), the CEC in the soil of the Manaus region, is due mainly to the organic part of the clay fraction.

The exchangeable aluminum of the soil was reduced as a function of the increase in the pH due to the addition of existing bases in the ash from the burned forest biomass and the polimerizing effect of heat on the soil aluminum. Similar information was obtained by Falesi (1976) and Baena (1978).

The P values in the soil under pasture of various ages were similar to those encountered in the forest soil.

Table 1. Average values of total exchange bases (S), cation exchange capacity (CAC), aluminum (Al), base saturation (V), aluminum saturation (Sat. Al), pH, and phosphorus (P) in soils (0-10 cm depth) of primary forest and *Brachiaria humidicola* pastures of various ages in a cleye Oxisol in Central Amazon

Ecosystem	S (meq/100 g)	CEC (meq/100 g)	Al (meq/100 g)	V (%)	Sat. Al (%)	pH (H_2O)	P (ppm)
Primary forest	0.42b	10.69a	1.54a	3.96b	79a	4.38b	2.3a
Slashed and burned primary forest	1.63a	9.78a	0.38b	16.66a	19b	5.25	–
1-year-old pasture	1.62a	10.18a	0.50b	16.00a	25b	5.18a	3.3a
2-year-old pasture	1.48a	a0.05a	0.67b	14.68a	34b	4.85ab	2.0a
6-year-old pasture	1.39a	a0.13a	0.55b	13.78a	31b	4.97ab	2.8a
7-year-old pasture	1.36a	10.37a	0.38b	13.04b	23b	5.20a	2.3a
8-year-old pasture	1.34a	9.32a	0.62b	14.37a	35b	5.08a	2.0a
Coeficient of variation	23.41	10.48	31.24	21.55	27.47	5.41	30.7%

Mean values followed by the same letter in the same column are not statistically different (Tukey test as 0.05).
(Adapted from Teixeira and Bastos, 1989.)

Table 2. Average values for organic C, OM, organic N and C/N relation in the soil (0-20 cm depth) of primary forest and pasture of *Brachiaria humidicola* of various ages in a claye Oxisol in Central Amazon

Ecosystem	C (%)	OM (%)	N (%)	C/N
Primary forest	2.62	4.55	0.18	15
1-year-old pasture	2.40	3.90	0.18	15
2-year-old pasture	2.10	3.45	0.16	13
6-year-old pasture	2.32	4.00	0.16	14
7-year-old pasture	2.48	4.25	0.19	13
8-year-old pasture	2.40	4.15	0.18	13

(Adapted from Teixeira and Bastos, 1989.)

In Table 2 the mean values for organic carbon, OM, organic nitrogen, and C/N in the 0-20cm layer in the ecosystems of primary forest and pasture of 1, 2, 6, 7 and 8 years found by Teixeira and Bastos (1989) are presented. The levels of organic C and for OM do not show any marked difference, mainly between the forest and the 1, 7 and 8 year-old pastures. These authors, while studying the soil to a depth of 1m, found 148 t/ha of organic C in the primary forest and 160 t/h in the pasture, attributing the higher values in the pasture to the deposit of some of the C that had been stocked in the forest biomass that stayed on the soil as residue.

The levels of N in the soil also show similar values in the ecosystems studied, scarcely altered by the burning of the forest vegetation.

The values for C/N were similar in the various ecosystems, and are found within the range of stability for arable soils. According to this relation, the pasture ecosystems do not appear to have immobilized the N already existing in the environment, probably due to the gradual deposit to the soil of new material from the pasture.

The values of apparent density (which is the most direct measure of compaction) in the soil under pastures of different ages did not show any significant difference when compared to the values for the forest soil.

Teixeira and Schubart (1988) studied the soil fauna that play an important role in the process of degrading organic material, by increasing the area exposed to the action of bacteria and fungus. The authors show that burning forest plant biomass causes the death of a great number of these micro organisms, thus reducing the faunal diversity of the soil. There was a great reduction in the number of faunistic groups in the recently burned soil. However, in the soil under the six year-old pasture, the number of animal groups doubled, but still remained below that found in the forest soil. In both the forest soil and soils under pasture, the groups of *Acari* and *Collembola* predominate in the number of individuals per m^2, corresponding to 78.06% and 84.77% for *Acari* and 9.79% and 7.72% for *Collembola*, respectively in the forests and pasture soils.

Although these experiments fail in relating the soil's physical and chemical changes to pasture productivity, they serve to indicate that adequately managed forest-replacing pastures in the Amazon may be appropriate land use systems for efficiently conserving soil nutrients and maintaining satisfactory physical conditions for plant growth.

B. Soil Transformation in Agroforestry Systems

Agroforestry systems have recently been promoted as alternative land use systems that will use land resources in the Amazon more efficiently (in a more sustained manner). They should, in some measure, gradually replace or be associated with present extensive low-sustainability land use systems such as open monoculture pasture-based cattle raising and shifting agriculture and may also be important in improving social and economic sustainability of extractive reserves.

Interesting forms of agroforestry systems are being developed in the Amazon, the most important and typical being those developed by Nippo-Brazilian farmers in the eastern part of the State of Pará (Subler and Uhl, 1990; Serrão and Homma, 1993). There are also an infinity of back-yard home-garden type systems carried out by small subsistence farmers all over the region (Fernandes and Serrão 1992).

Due to their present and potential importance for increasing sustainability of agricultural and forestry development in the region (Serrão and Homma, 1993), there is an increasing interest in research for developing sustainable agroforestry systems through domestication and introduction of high-value, multi-purpose native and exotic trees and food crops for development and management of integrated crops and trees.

Unfortunately, very few experiments have been designed to evaluate the effect of these systems on modifications of soil resources. Next, the most important research attempts which may be characterized as long-term experiments will be briefly described.

For the purpose of this paper, the following five agroforestry combinations were selected (because of their present and potential importance) from a large-scale experiment being carried out at an EMBRAPA-CPATU experimental station in the eastern part of the State of Pará, where dense rain forest is the dominant natural vegetation, medium-texture Oxisol is the predominant soil type and the Am climate of the Köppen classification prevails. The agroforestry combinations were planted in 1977 after the usual slashing and burning of the forest in the second half of 1976.

1. Agroforestry System 1: Traditional Cocoa (*Theobroma caco*)/Erythrina (*Erythrina glauca*) Association in Capitão Poço, Pará.

In this system, temporary (banana) and permanent (erithryna) shading plants were planted in 1977, spaced at 2.5 m x 2.5 m and 10.0 m x 10.0 m respectively, and cocoa seedlings were planted in 1977.

In a 12-year period (1978-1989), the system received fertilization which corresponded to approximately 70 kg N, 40 kg P, 84 kg K, 25 kg Ca, and 12 kg Mg per hectare annually. Table 3 shows that there were changes in soil fertility due to fertilizer application. Initially, a decline in soil OM was observed, but, after the seventh year of the cropping system, the trend was one of increase in soil OM content. Although there was no definite trend in soil pH values with time, they were always higher under the crop system than under the forest. The relatively high value of Ca + Mg in the planting year (1977) is attributed to the liming effect of slashing and burning in 1976 (the same positive effect can be said in relation to soil pH and Al). Two years after planting, a decline in soil Ca + Mg was observed, but this trend moved toward higher levels after the application of lime in 1984, which also resulted in maintaining Al at low levels, almost to the point of neutralization.

The level of P in the soil did not suffer significant alterations after cutting and burning the forest biomass. With the application of fertilizers in 1978, the level of P in the soil had a considerable increase in relation to the levels found after burning, and since 1982, the levels of P have remained at constant levels. The P fertilizer application was only to replace those nutrients lost due to cocoa fruit production and harvest. On the other hand, even with annual applications, K was present in the soil at low levels. This is explained by the fact that K is required for fruit production and is also lost through leaching of the soil (EMPRESA...1990).

Table 3 shows that the production of cocoa was high in the first three years, but dropped significantly in the years 1985 and 1986. From 1987, the cocoa production reached higher levels, corresponding to higher levels of soil K.

2. Agroforestry System 2: Cocoa/Peach Palm (*Bactris gasipaes*) Association in Capitão Poço, Pará

In this system, cocoa seedlings (spaced at 2.50m x 2.50m) and the permanent shading plants of peach palm (spaced at 10m x 10m) were planted in early 1978 following planting of the temporary shading plants (banana) in 1977.

In this system, in the 1978-1989 period, annual fertilization corresponded to approximately 76 kg N, 50 kg P, 102 kg K, 30 kg Ca, and 15 kg Mg, somewhat higher than in Agroforestry System 1, due to additional fertilization to peach palm trees.

Phosphorus was the soil nutrient that was most altered under the agroforestry system in relation to the forest soil. Soil P content was maintained at medium

Table 3. Productivity under five agroforestry systems

Year	Cocoa production in cocoa/erythrina association	Cocoa/peach palm system		Cocoa/rubber system		Rubber production in tree system	Rubber production in kudzu system	
		Cocoa	Peach palm	Cocoa	Rubber		with fertilizer	without fertilizer
1982	1548	1473	-----	-----	-----	-----	-----	-----
1983	1797	1415	-----	-----	-----	-----	-----	-----
1984	2002	2241	7075	-----	-----	-----	-----	-----
1985	974	1048	8400	1705	-----	-----	-----	-----
1986	939	1788	6920	1648	-----	-----	420	140
1987	1167	1308	7060	1185	350	505	1020	220
1988	1216	1559	5809	1819	321	510	810	405
1989	1271	1691	6400	914	237	423	795	380
1990	1361	-----	-----	1514	300	420	-----	-----
1991	-----	-----	-----	-----	414	427	-----	-----

to high levels in the crop system over the years. Soil K was low in the system during the first 6 years, but increases to medium levels thereafter.

The soil content of Ca + Mg increased after the clearing and burning of the forest biomass, then showed some decline in the first four years of the system and increased beginning in the fifth year. It can be observed that Al content in the soil was considerably lower in the agroforestry system, initially due to the liming effect of burning of the forest biomass and, after 1987, due to lime application that year. As a result of the initial clearing and burning, pH values also increased and were maintained always higher than in the forest soil.

The contents of the soil OM also showed decreases after cutting and burning, falling to 50% from that observed in the forest soil in 1981. However, from the seventh year the system showed a gradual increase in the OM content and by 1990 had reached the same levels as had been observed in the forest soil.

Average yields of cocoa and peach palm can be considered high in relation to those observed in average commercial production systems in the region. In this case, there seems to be no significant relation between cocoa and peach palm productivity and soil fertility parameters. According to Silva & Dias (1987), in general, there is no interference in the yield of both cocoa and peach palm in mixed systems, as long as peach palm tree density is not superior to 130 plants per hectare.

3. Agroforestry System 3: Cocoa/Rubber Tree (*Hevea* sp) Association in Capitão Poço, Pará

Similar to the agroforestry systems 1 and 2, banana trees were used as temporary shade and rubber trees (5m X 15m spacing) were planted in 1977; followed by cocoa (2.5m X 2.5m spacing) in 1978. Annual fertilization of the system during the 1978 through 1990 period corresponded to an annual application of 64 kg N, 36 kg P, 78 kg K, 25 kg Ca, and 11 kg Mg per hectare.

The low soil P content observed under the forest increased considerably in the soil of the agroforestry system during the first few years after slash-and-burning and then declined to somewhat lower levels which were maintained over the years.

Soil K was maintained at low levels in the agroforestry system through the years after a slight increase in the first couple of years following slash-and-burning. Toward the end of the period, soil K levels in the system became as low as those found in the forest soil.

The drop in the levels of P and K in the soil of the agroforestry system was associated with the beginning of cocoa production, a tropical crop with high nutrient demands, requiring large quantities, mainly of K, as shown by Morais (1988) and Relatório (1992).

The levels of Ca+Mg in the soil of the agroforestry system were well above those observed in the forest soil, with higher levels in the years from 1983 to 1985. Afterward they showed a decline, and then stabilized at values found in the first years of the system. Soil Al was reduced with the liming effect of the forest biomass burning and was maintained at low levels in the system through the years with a slight increase toward somewhat toxic levels at the end of the period. Conversely, pH values raised with slash-and-burning and were maintained over the years in the soil under the system.

Soil organic matter content was reduced (in relation to forest soil) with biomass burning, maintained at low levels during the first few years in the system, and increased after the 6th year, being maintained at levels close to those found in the soil under the forest.

In relation to the physical characteristics of the forest soils and the agroforestry system, Costa and Teixeira (1992) found apparent densities in the soil under primary forest varying from 1.53g/cm^3 in the 0-20-cm layer to 1.45g/cm^3 in the 100- to 150-cm layer. In the soil under the agroforestry system the variation of apparent density was 1.55g/cm^3 in the 0-20cm layer and 1.47g/cm^3 in 100- to 150-cm layer , while the water retention capacity in the soils under forest and under the agroforestry system were similar. This data shows that after 14 years of substituting the forest with an agroforestry system, there has been practically no physical change in the soil.

Cocoa production was variable but within expected limits, except in 1990 which has some coincidence with the observed low soil content of P, K, and Ca + Mg. But a similar trend was not observed in rubber production.

4. Agroforestry System 4: Rubber Tree as a Monocrop in Capitão Poço, Pará

In this system, rubber tree seedlings were planted in 1977, 2.5m apart within rows 7.5m apart from each other. Annual fertilization in the 13-year period (1978-1990) corresponded to approximately 38 kg N, 16 kg P, 77 kg K, 8 kg Ca, and 5 kg Mg per hectare.

All soil parameters were significantly altered after slash-and-burning. Soil P was maintained in the system at adequate levels after the third year, but showed a reduction toward the end of the period. The same pattern was observed for soil K.

Soil content of Ca + Mg was initially low in the system but tended to increase with time. Conversely, soil Al was reduced with the liming effect of burning and was maintained at very low levels in the system over the years. Soil pH had similar patterns to that of Ca + Mg and, over the years in the system, was maintained at satisfactory levels, acidity being considerably lower than in the forest soil. As for soil OM, its tendency was one of reduction in the first few years in the system with a tendency to increase with time, in general, with higher values than in the forest soil. In spite of some reduction in the soil P and K content towards the end of the period, apparently these reductions were not sufficient to reduce rubber yield in the system.

shows that from 1986 through 1989, average annual dry rubber production in the fertilized system was almost three times higher than in the unfertilized system.

The levels of K are lower in the systems with rubber trees than those of the forest soil, but, from the third year on, the values for K have been above those observed in the forest.

The transformation of primary forests to cultivated agroecosystems, hardly alters the physical parameters of the soil. Chemical parameters are positively affected in relation to the forest soils, mainly in relation to P, K, and Ca+Mg. The sustainability of these systems in terms of nutrients can only be achieved with the application of fertilizers, mainly P and K, to replace the quantities used by production and lost through leaching.

Of the five agroforestry systems presented, the agroforestry systems 2 (cocoa in association with peach palm) and 3 (cocoa in association with rubber trees), are shown as the most viable alternatives for small and medium producers that, traditionally, plant subsistence crops. The use of these systems will provide capital which will give year-long income from the marketing of rubber, cocoa and peach palm, besides promoting social forestry which are agro-technically and economically sustainable.

C. Soil Transformation in Silvopastoral Systems

Although in their initial stages of development in the Amazon and still mostly concentrated in the eastern Amazon in small- and medium-size properties, where Veiga and Serrão (1990) found several associations of fruit and timber trees with a wide strata of grasses and legumes for cattle raising, silvopastoral systems are promising land use systems for improving agricultural sustainability in the Amazon.

These systems have only recently attracted the attention of researchers because there is potential for increased agrotechnical, environmental, and socioeconomic sustainability. Only one known research attempt has been made to study silvopastoral systems in the Amazon, and is summarized as follows.

Silvopastoral systems: An association of forest species with forage grasses for reclamation of degraded pasture lands in the Eastern Amazon.

This research was developed in a degraded commercial pasture area on a large private ranch in the county of Paragominas, State of Pará. The original vegetation of the area was a dense rain forest, the predominant climate is a transition between the Am to the Aw climate type of the Köppen classification. The soil of the area is predominantly heavy-clay Oxisol (Yellow Latosol) with naturally high acidity and low fertililty (Falesi, 1976). The land was cleared and burned for pasture establishment with guineagrass in the early 1960s. After a few years of relatively high productivity, the pasture went through the process of degradation as briefly described before in this paper.

The degraded pasture area was mechanically prepared (windrowed and disked) in 1984, and in early 1985 the experiment was planted with the following design: The experimental area was divided into three blocks of approximately 3 ha each. In each block, one grass (out of three grasses selected, namely: *Brachiaria humidicola, B. brizantha*, and *B. dyctioneura*) was planted in association (actually, in 12m-wide strips between the three-line rows of tree species) with each of three forest species, namely: *Eucalyptus teriticornis, Schyzolobium amazonicum* and *Bagassa guianensis*.

In 1985, the forest species were planted together with corn which was harvested the same year. In 1986, corn was again planted between the tree rows. This operation was again repeated in 1987, this time together with the forage grasses. Steers were used to rotationally graze the plots at the stocking rate of one head per hectare to introduce the grazing effect on the system

The growth of the trees was considered to be very satisfactory, especially that of *S. amazonicum*, and *E. teriticornis*. As for the associated grasses, excellent establishment and growth was observed in *B. brizantha,* and, secondarily but still with adequate performance, in *B. humidicola* and *B. dyctioneura.*

Soil samples (0-20 cm depth) for determining the chemical and physical composition of the soil in the different pasture/tree combinations were taken twice a year in the wet and in the dry seasons from 1986 through 1990. The following comments on soil change with time are based on average (of wet and dry season) annual soil composition.

The experiment was interrupted in the second semester of 1991 because of an accidental fire which damaged the forest species mainly.

Ca + Mg in the *B humidicola* plots had a tendency to decline the same trend was observed in the *B. dyctineura* area. A peak was observed in *B. humidicola* area in 1989, possibly due to the mineral supplementation which was supplied to the grazing cattle in all plots, but which may have been localized at sampling time, thus influencing the soil analysis, in comparison with the other treatment combination.

Soil K tended to decline in the soil under all grass species after four years of grazing. Probably, most of this is due to the K going out of the system in the consumed grass forage and some is probably leached from the soil surface.

Apparently, the tree-grass combinations were not able to retain enough carbon in the soil through the years, a reduction of about 20% being observed from 1986 to 1990.

Soil P seemed to increase in the pasture, except for the *B. humidicola* pasture. This increase seemed to be related to the mineral supplementation offered to the cattle in all pastures, which is probably higher than the P removed from the pasture through the consumed grass forage. Besides, P is considered a nutrient practically immobile in the soil.

Soil Ca + Mg contents were similar (around 5 mg/100g) under the trees through time until 1989, but showed some differentiated reduction in the 1990 sampling. Loss of K under the trees with time was more accentuated than that of Ca + Mg, probably because K is a more leachable mineral in the soil and is removed in higher quantities in the consumed grass than Ca and Mg. Reduction of soil K was about 30 % under the trees.

Soil C losses were practically the same under all three timber trees (about 20%), similar to those in the soil under the grasses. However, soil C content was above 2% (3.4% OM) which can be considered satisfactory for kaolinitic soils in the Amazon in which OM is responsible for 70% of the cation exchange capacity (CEC).

Similar to the soil under the pastures, P content under the trees had a considerable increase with time (explanation can be the same for the soil under grass strips) but the levels are still low as usual under these land use conditions.

In general, the soil under the tree-grass combination had a decline in its content of most nutrients with time except for small increases in P content but still at low, deficient levels. However, Ca, Mg, K and C were still at satisfactory levels, except for K in the grass strips which has probably started to become limiting for tree and grass growth.

As far as the soil moisture content was concerned, a general trend with time was of slight increases in the soil under the grasses and under the timber trees, and were more noticeable under the trees, as expected.

Although the experiment discussed give some indication of the trends in soil chemical and physical transformations in agrosilvopastoral systems, much needs to be learned from long-term, well-planned agrosilvopastoral experiments.

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