SOIL AND DEVELOPMENT IN AMAZONIA: LESSONS FROM THE BIOLOGICAL DYNAMICS OF FOREST FRAGMENTS PROJECT

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ABSTRACT

Soils data from the 1000-km^2 area covered by the Biological Dynamics of Forest Fragments (BDFFP) reserves (north of Manaus, Amazonas) provides detailed information of the type used in development planning, such as the economic-ecological zoning of the region now being carried out by the Brazilian government. The soil in the reserves is typical of vast areas of Brazilian Amazonia that are likely to be increasingly deforested for agriculture and ranching. These soils have low fertility, are acid and have high levels of toxic aluminum ions. They also have limitations due to topography, generally very high clay content, and low values of available water capacity. Agricultural potential is low, and the prospects for resilience are not bright given the reality of changing land-use patterns in the region. The soils under forest also give indications of the environmental impact of converting these areas to pasture and other uses, including the potential for release of greenhouse gases (which depends on forest biomass, a feature related to distribution of natural vegetation and favorability of soils for plant growth), the probable response of forest to fragmentation, and the probable response of forest to climatic change. Our soils research indicates that areas like this would produce little if converted to agriculture or ranching, and point to land uses that maintain forest cover intact as preferable. The value of the environmental services provided by the standing forest far exceeds the returns that can be expected from clearing it for agriculture or ranching.

I.) INTRODUCTION

A.) RELEVANCE OF SOILS TO PLANNING

Soil quality is obviously fundamental to the potential of any area to produce and sustain agricultural yields. If planning decisions are made to encourage agriculture in areas with soils that are not suited to this purpose, crops can be expected to fail. Planning decisions opening vast areas to settlement are frequently made in a near vacuum of information on soils. For example, when the POLONOROESTE Project opened Rondônia to settlement through a World Bank-financed regional development program centered around paving the BR-364 (Cuiabá-Porto Velho) Highway, the soils information available for Rondônia (Brazil, Projeto RADAMBRASIL, 1978: Vol. 16) was based on only 85 soil cores. Such events are recurring today quite near the Biological Dynamics of Forest Fragments Project (BDFFP) reserves: on 24 June 1997, president Fernando Henrique Cardoso announced in his weekly radio program "Palavra do Presidente" that six million hectares (ha) along the BR-174 (Manaus-Caracaraí) Highway would be opened to settlement, and suggested that the area farmed there would be "so colossal that it would double the nation's agricultural production" (de Cássia, 1997). Despite almost certain hyperbole in both the expected production and the area likely to be settled, the intention of initiating a major program on the BR-174 Highway appears to be real. The announcement of the BR-174 settlement program came as a surprise, as the paving of the highway (in 1996 and 1997) had been presented as a surgical cut through the forest that would allow the city of Manaus to trade with Venezuela and have access to that country's ports.

Neither studies of soils and agronomic potential nor assessment of environmental impact were done prior to the announcement of the BR-174 agricultural project. As is true for most of Brazilian Amazonia, information on soils used in planning is essentially restricted to the results of the RADAMBRASIL Project, which, in the early 1970s, mapped soil, vegetation and other features based on side-looking airborne radar (SLAR) imagery (Brazil, Projeto RADAMBRASIL, 1976: Vol. 10, 1978: Vol. 18). Original imagery was at a scale of 1:250,000 and was published at a scale of 1:1,000,000. Areas with the same appearance on the images were mapped as the same, with field checking to identify vegetation and soil in many of the units. The BR-174 area has been identified by the Amazonas state government as a priority for economic-ecological zoning (Pinheiro, 1997).

The portion of the BR-174 to be opened for agriculture lies over the Guianan Shield, and can therefore be expected to be more fertile than those in the BDFFP reserves. However, the Landless Rural Workers' Movement (MST) has recently invaded some ranches in the SUFRAMA (Manaus Free Trade Zone Superintendency) Agriculture and Ranching District (not those under study by the BDFFP), raising the possibility that some of these ranches may be distributed to small farmers for agriculture (Pacífico, 1997).

B.) SOIL CLASSIFICATION

The BDFFP reserves are located 80 km north of Manaus (2°30'S, 60°W), and are spread over a 20 X 50 km (1000 km^2) area. The site is approximately 25-50 m above mean sea level; mean annual temperature at Manaus is 26.7°C and mean annual rainfall (30-year average) is 2186 mm with a three-month dry season lasting from July to September (Lovejoy and Bierregaard, 1990). The site of the BDFFP reserves is typical of much of central Amazonia.

The RADAMBRASIL maps classify the BDFFP reserves as allic yellow latosols, which are Allic Haplorthoxes (Oxisols) in the US soil taxonomy and haplic or xanthic Ferralsols in the FAO/UNESCO system (see Beinroth, 1975). The classification as a latosol(1) relates to the type of clay minerals present. The relative amounts of clay minerals composed of silicate (kaolinite), iron (goethite) and aluminum (gibbsite) determine the structural stability, the natural fertility and the effect of applying fertilizers (Sombroek, 1966: 73).

Oxisols are the most common soil in the Amazon Basin, covering 220 million ha or 45.5% of the total (including areas outside of Brazil); most of the remainder is covered by Ultisols (such as the red-yellow podzolic soils of the Brazilian system), covering 142 million ha or 29.4% (Cochrane and Sánchez, 1982: 152). Oxisols are distinguished from Ultisols by lack of higher clay content with depth; Ultisols have at least a 20% increase in clay content in the lower (B) horizon (United States, Department of Agriculture, Soil Survey Staff, 1975). At a high level of generality, Ultisols are considered less appropriate than Oxisols for mechanized agriculture due to susceptibility to soil compaction and their frequent occurrence on more steeply sloping terrain (Sánchez, 1977: 539). However, the broad range of characters within either of these great groups (as illustrated, for example, by the results of the present study) indicate the need for caution in applying such generalizations to specific management decisions (see Fearnside, 1984).

Oxisols and Ultisols (i.e., yellow latosols and red-yellow podzolics) often occur in close proximity in Amazonia and frequently intergrade with each other (Sombroek, 1966: 68). Profiles in nearby sites confirm this (Chauvel, 1982; Ranzani, 1980). However, since both Oxisols and Ultisols are similar in being acid, infertile soils that are indistinguishable from each other without information on differences in the B horizon (which is outside the rooting zone of most crops), taxonomic differences between them generally have little relevance for agriculture as practiced in Amazonia.

The BDFFP reserves are located about 50 km south of the edge of the Guianan Shield (the Balbina hydroelectric dam is located at the edge of the Shield). The reserves are within the basin bounded by the Brazilian and Guianan Shields. This basin covers approximately 1.2 X 10^6 km^2 in Brazil, or about 25% of Brazil's 5 X 10^6 km^2 "Legal Amazon" region. It is known as the Alter do Chão Formation (formerly called the Barreiras Formation). The soils are derived from sedimentary deposits from the bottom of a shallow sea that occupied the center of the Amazon Basin during the Tertiary (Falesi, 1974; Jordan, 1985). The soils derived from these sediments have been exposed to heavy rainfall and high temperature over most of the approximately 60 million years since the region was uplifted at the time that the Andes mountains were formed; most of the nutrients have therefore been leached out of the soil (Sombroek, 1984). Younger soils, such as those derived from igneous rocks in the Guianan and Brazilian Shields, have higher fertility than those of the BDFFP area, although they too are far from being classed as fertile for agriculture.

The general characteristics of the origin of soils are closely associated with their overall fertility. In the case of the BDFFP area soils, this history rules out occurrence of high-fertility soils, with the exception of patches of anthropogenic black soil (terra preta do índio), which was not found in the project area. However, great variation in some characters occurs within any given area, such as the BDFFP reserves, that appears as uniform at the scale considered by the RADAMBRASIL survey (the maximum level of detail that can presently enter land-use planning decisions); in reality, not even this level of detail is considered when many actual decisions are taken. Perhaps the clearest example of this was the complete ignoring of existing soil maps when government decisions were taken on the location of settlement areas in agriculturally unpromising areas of Rondônia (Fearnside, 1986a).

C.) SOIL VARIABILITY

The BDFFP soil survey offers a unique opportunity to assess fine-scale variability in Amazonian soils and the potential significance of this variability for development planning. Fine-scale variability can be expected to affect agricultural success; it also affects the natural vegetation, both in influencing what trees (and thereby other life forms) occur and the stress placed on those trees when they find themselves isolated in forest fragments.

Variability in initial soil quality, as well as in other factors, is a key determinant of human carrying capacity (Fearnside, 1986b). In the Transamazon Highway colonization area, for example, soils vary from fertility levels similar to those found in the BDFFP area to considerably higher levels in terra roxa (Alfisol) areas, as well as in much smaller patches of terra preta do índio (anthropogenic black soil) (Fearnside, 1984). The occurrence of fertile patches, even if small in area, is important in the success of colonist agriculture, as is the ability of farmers to identify these patches by knowledge of the tree species that typically grow on them (Moran, 1981).

D.) ECONOMIC-ECOLOGICAL ZONING

Brazil's 1988 constitution calls for zoning of the entire country, after which land-use decisions for each area would have to be made in accord with the zone assigned to it. This provision was supported by the "environmental caucus" of constitutional delegates, and was viewed as a great victory for increasing the amount of protection against excessive environmental impacts of development modes such as those that result in tropical deforestation. However, the question of zoning soon became a controversial one, with those who implement zoning at the level of state governments often viewing it more as a means of "opening up" areas to development rather than as a means of containing development excesses (see Fearnside and Barbosa, 1996, for examples from Roraima).

Following the October 1988 constitution, an inter-institutional struggle ensued for control of the zoning at the federal level; the principal contenders were the Brazilian Institute for Geography and Statistics (IBGE), the Brazilian Enterprise for Agriculture and Ranching Development (EMBRAPA), and the Ministry of Science and Technology (MCT) (Régis, 1989). The matter was settled by a 1991 presidential decree giving responsibility to the Secretariat for Strategic Affairs (SAE), which had formerly been known as the National Information Service (SNI): a much-feared internal espionage agency. This institutional setting can potentially affect both the priority assigned to environmental concerns and the degree of popular participation in the zoning process.

The methodology to be used in the zoning has been the subject of long controversies. A series of very general maps was prepared at a scale of 1:2.5 million using data from the RADAMBRASIL surveys; additional data collection was not undertaken for these "diagnostic" maps, but some additional data collection is foreseen in state-level zoning projects. The zoning projects and the strengthening of the state-level agencies that have begun to carry them out is being done with assistance from G7-Pilot Program to Conserve the Brazilian Rainforest (with funds administered by the World Bank).

Increasing the level of detail of data on characteristics such as vegetation and soils is obviously important in order to increase the degree of confidence in zoning conclusions. It is also important to achieve a better understanding of how to scale down from general zoning maps to the fine-scale variation that exists on the ground where development actually takes place. One approach proposed to interpreting soils information in conjunction with information on vegetation, topography and other features is the "land units" approach (Sombroek, 1966; see Sombroek et al., 1999). Land units use naturally co-occurring sets of these characters as the basis for defining the categories into which the landscape is divided for purposes of planning.

E.) IMPORTANCE OF SOIL PROPERTIES

1.) Soil texture

One of the most important characteristics of the soil is its texture: for example, the balance between sand and clay fractions. Very sandy soils are poor for plant growth because they lack sites for holding cations (which are consequently leached away, leaving the soil infertile), and because sandy soils do not hold water well, exposing plants to drought stress during dry periods. Clays have more sites for cations, largely because clay content is positively correlated with organic matter when comparing surface samples taken at different locations (as distinct from comparisons made between different depths in the soil profile). Clay also holds cations directly, independent of its effect on organic matter. Organic matter is especially important in contributing to cation exchange capacity (CEC) in soils with clay minerals of low activity, such as the Oxisols and Ultisols of Amazonia (Lenthe, 1991: 121). Cation exchange capacity is a measure of the negatively charged sites on the surfaces of clay and humus molecules; these sites may be occupied either by nutrients needed for plant nutrition (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) or competing ions in acid soils (H^{+}, Al^{3+} and Fe^{2+}, but only the first two of these are included in the CEC).

Clays also hold water better in the smaller pores in the soil matrix. However, very heavy clays can have disadvantages because they have a higher proportion of very small micropores from which removing water requires an undue exertion of force by the plant roots (i.e. water requires a tension of more than 15 atmospheres to remove). The large percentage of water at tensions above 15 atmospheres (bars) in very clayey soils, which can be as high as 30% by weight, has a positive role as well: it increases the stability of organic matter, contributing to the positive relationship between clay content and organic matter (Bennema, 1977: 35). The relationship between clay and plant growth can be complicated by the effect of aluminum ions, which are toxic to most plants in high concentration. The allic (high aluminum) clays that are common in Amazonia lead to a strong positive correlation between clay content and aluminum. Because most of the effects of clay are beneficial to plants, one can expect a positive association between aluminum and plant growth even though the effect of aluminum per se is negative.

Excessively heavy clays can also pose a physical impediment to the growth of tree roots. Soils for citrus trees, for example, are considered best if they have a mix of sand and clay rather than being pure or almost pure clay. For cacao, the best soils have 30-40% clay, 50% sand, and 10-20% silt (Smyth, 1966 cited by Alvim, 1977: 289). The various effects of clay content on plant growth are summarized in Figure 1. In causal loop diagrams such as this, the sign at the head of each arrow indicates the direction of change in the quantity at the head of the arrow given an increase in the quantity at the tail of the arrow.

[Figure 1 here]

Clay content of the surface soil is relevant to the susceptibility of soils to erosion, particularly laminar (sheet) erosion (see Fearnside, 1980). Clay, being composed of particles of the smallest dimensions, is more easily carried away by runoff water than are coarser particles such as sand. Clay can make the soil less permeable, leading to greater amounts of runoff for a given amount of rainfall, but in well-aggregated clay soils, such as those in the BDFFP area, drainage can be good despite high clay contents. In typical yellow latosols (Oxisols) the soil aggregates are not covered with silicate clay skins or linings, and the soils are little subject to gully erosion (Sombroek, 1966: 77). Oxisols with low iron content (a feature indicated by the yellow color of the BDFFP reserve soils) are the ones most susceptible to topsoil deterioration when exposed to sun and rain under agriculture, making them more susceptible to erosion when the surface becomes impermeable and runoff consequently increases (Bennema, 1977: 35).

2.) Available water capacity

"Available water capacity," also known as "available water," is a measure of the amount of water that the soil can hold in a form that can be extracted by plant roots. It is calculated as the difference between field capacity (total moisture content of soil after gravity water has been allowed to drain away) and wilting point (the moisture content at which plants wilt and do not recover on re-wetting) (Young, 1976: 40). Water held in fine pores cannot be extracted from the soil at the pressures that plants are able to exert through their roots. Field capacity is determined at 0.33 atmospheres (bars) of tension, and wilting point at 15 bars.

The available water capacity calculated by this standard procedure is really only an index of availability for several reasons. One is that the ability of plants to extract water from the soil varies among species, which may differ from the sunflower--the plant taken as a standard by soil scientists. A second is that the 0.33 bar pressure used as a standard operational definition of field capacity underestimates water holding capacity: 0.1 bar is believed more appropriate, meaning that the standard method leads to an underestimation of available water capacity by about 35% (Sánchez, 1976: 111). A third is that intact soil cores taken from the side of a soil pit are the ideal material for the measurements, and results using dried material from traditional soil samples (as in the present study) provides only an indication of these parameters in the field.

Some indications exist that available water capacity may pose a restriction on use of water by the forest in soils similar to those in the BDFFP reserves. A study of undeformed cores in INPA's "Model Basin" (30 km south of the BDFFP reserves) indicated that, while pores make up 60% of the soil volume at 10 cm depth, only 17% of the water contained in the pores is available to plants, while 50% is bound water and 33% is lost at a pressure less than 0.33 bar and drains away by gravity (Ferreira, 1997: 168).

3.) Phosphorus

Phosphorus is a limiting element for agricultural crops and cattle pasture in Brazilian Amazonia. For example, P fertilization is the key to increasing pasture grass growth in technical packages formulated by EMBRAPA (e.g. Koster et al., 1977; Serrão et al., 1979). Phosphorus is low in virtually all soils in Brazilian Amazonia, even including relatively fertile ones such as the terra roxa (Alfisol) occurrences in settlement areas along parts of the Transamazon Highway in Pará and the BR-364 Highway in Rondônia (see Fearnside, 1984, 1986b). Furthermore, the prospects are poor for maintaining vast areas of agriculture dependent on phosphate fertilizer in Amazonia because of limited deposits of rock phosphate in Brazil and worldwide; virtually all of Brazil's modest supplies of this mineral are located outside of Amazonia (see de Lima, 1976; Fenster and León, 1979; Fearnside, 1997a,b; Beisiegel and de Souza, 1986).

It is available phosphorus (PO_4, actually the anion $H_2PO_4^-$), rather than total P, that is most directly related to plant growth. Phosphorus availability in latosols is generally very low because most of it is in highly insoluble Fe and Al compounds (Kamprath, 1973a: 139). Phosphorus availability in agriculture is usually stated in terms of phosphoric anhydride (P_2O_5); considering analyses made with the North Carolina extractant (0.05 N HCl and 0.025 N H_2SO_4) that is standard in Brazil, 1 milliequivalent (m.e.) of PO_4^{3-}/100 g of dry soil is equal to 103 parts per million (ppm) of P or 23.7 mg of P_2O_5/100 g of dry soil (e.g., Vieira, 1975: 451-453). While the total soil P obviously sets a limit on the amount of available phosphorus that can be present, a variety of soil characteristics and processes determine the available phosphorus present within this limit. Values of pH below 5.5 are generally associated with marked decrease in phosphorus availability (Young, 1976: 299). Organic carbon and Fe_2O_3 both are positively related to available phosphorus (P_2O_5) in Brazilian Oxisols (Bennema, 1977: 43). Since both carbon and iron are associated with high clay content, the granulometric structure of the soil relates to plant growth through phosphorus, as well as through other nutrients and through water. Micorrhizae are important in mobilizing P into available forms (St. John, 1985). Micorrhizal associations have been found in many, but by no means all, of the few Amazonian trees that have been examined (St. John, 1980).

4.) pH, aluminum and cations

Little information exists on the response of Amazonian trees to different soil characters. One important exception is the case of cacao, which is a native Amazonian tree that has been the subject of much more research than other species due to its economic importance. It is noteworthy that, while most Amazonian trees appear to be highly tolerant of very acid soils, soil pH (soil reaction) is the best predictor of cacao yields (Hardy, 1961; see Fearnside, 1986b). Under the acid conditions that prevail in most Amazonian soils, soil pH is the single most important influence on yields for many crops, such as maize (see Fearnside, 1986b). In agricultural settings, soil pH at the time of planting is dependent not so much on the initial pH of the soil as on the quality of the burn that the farmer obtains when preparing the land for planting (Fearnside, 1986b). The relations of soil pH to plant growth are included in Figure 1.

Cation exchange capacity of soils rich in iron and aluminum oxides (such as those of the BDFFP reserves) is pH dependent (Young, 1976: 95). In addition, low pH leads to increased concentrations of ions that are toxic or useless to plants (Fe^{2+}, Al^{3+} and H^+), which occupy some of the reduced number of binding sites that do exist. "Base saturation" is the percentage of the sites that are occupied by useful cations, or exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+, the sum of which is "total exchangeable bases"). Cation exchange capacity is normally calculated as total exchangeable bases + Al^{3+} + H^+, all in units of m.e./100 g of dry soil (Guimarães et al., 1970: 85). Cation exchange capacity, total exchangeable bases and base saturation are, in practice, often calculated without data on Na^+ (e.g., Young, 1976: 426-429); the results are little altered as sodium ions are normally present in low and fairly constant quantities (around 0.01 m.e./100 g of dry soil).

The importance of low pH to agriculture is often due to its close relationship to toxic aluminum ions (Al^{3+}). Aluminum ion concentration normally has a negative logarithmic relationship with pH (see Fearnside, 1984; Sánchez, 1976: 225). It is generally believed that aluminum saturation, rather than the absolute concentration of aluminum ions, is most closely related to plant growth (Primavesi, 1981: 100). Aluminum saturation can be computed in two ways, with or without including exchangeable acidity (H^+). Including H^+, the sum of Al^{3+} + H^+ is divided by the total exchangeable bases plus Al^{3+} and H^+, and the result is expressed as a percentage (Sánchez, 1976: 224). This is the same as 100% minus the base saturation, so only one or the other need be used in analyzing relations with plant growth when defined in this way. In Brazil, however, aluminum saturation is usually calculated without H^+, it being Al^{3+} divided by the exchangeable bases + Al^{3+}, expressed as a percentage (Brazil, SNLCS-EMBRAPA, 1979). Aluminum saturation calculated in this way of over 25% indicates inhospitable soils for cacao (Alvim, 1977: 291).

Crops vary widely in their sensitivity to aluminum toxicity: in terms of aluminum saturation with H^+, maize can tolerate up to 60% aluminum saturation, while sorghum is restricted even at very low levels of aluminum saturation (Sánchez, 1976: 231). Aluminum ions also have a detrimental effect as one factor affecting fixation of phosphorus into unavailable forms (Kamprath, 1973b: 127). Aluminum toxicity itself acts partly through phosphorus, as aluminum tends to accumulate in the roots and impede uptake and translocation of both P and Ca to the aerial portion of the plant (Sánchez, 1976: 231). Aluminum in the soil solution depends not only on pH but also on organic matter content of the soil: aluminum ions decrease as organic matter increases because organic matter forms strong complexes with aluminum (Sánchez, 1976: 226).

The difference between pH in potassium chloride (KCl) and water, or delta pH, indicates the charge status of an oxide system (a soil in which entire clay particles consist of iron and aluminum oxides, or allophanes, or a soil in which stable coats of these oxides cover silicate particles)(Sánchez, 1976: 140-141). If pH in KCl is less than that in water (delta pH is negative: the usual case), then there is a net negative charge (cation exchange capacity), whereas if the reverse is the case there is a net positive charge (anion exchange capacity). The magnitude of the charge affects the soil pH at the isoelectric point, or zero point of charge. This, in turn, determines the cation exchange capacity (CEC) at any given soil pH level.(2) The organic matter content of the soil has a strong influence on these relationships and resulting CEC (Bennema, 1977: 39; Sánchez, 1976: 146). Delta pH is often used as an indicator of organic matter. If pH in KCl is higher than pH in H_2O (delta pH is positive), then organic matter is low. Delta pH is normally positively associated with C/N ratio in Amazonian soils, especially when disparate soils are compared with wide differences in delta pH values (Tanaka et al., 1984: 55).

5.) Nitrogen

Nitrogen is traditionally considered to be the major nutrient deficiency in tropical agriculture (National Academy of Sciences, 1972: 8; Webster and Wilson, 1980: 220). Leguminous trees are able to fix nitrogen with the aid of symbiotic bacteria, which probably gives members of this superfamily a competitive advantage over species in families that lack this capability. This helps explain why legumes are a common group in the BDFFP reserves, but hardly a dominant one: Burseraceae, Sapotaceae and Lecythidaceae are all more common (Rankin-de-Merona et al., 1990: 574). In a model developed by the BIONTE (Biomass and Nutrients) project for INPA's "Model Basin" (located on the same soil type about 30 km south of the BDFFP reserves), N was assumed to be limiting for the forest as a whole (Biot et al., 1997: 284). In the BDFFP reserves, total N was found to be positively correlated with forest biomass (Laurance et al., 1999).

Sollins (1998: 23) reviews literature on relation of soils to lowland rainforest composition, and suggests that soil factors in decreasing order of importance would be: P availability, Al toxicity, depth to water table, amount and arrangement of pores of different sizes, and availability of base-metal cations, micronutrients (e.g., B, Zn), and N. Nitrogen is listed last because most lowland tropical soils are relatively N-rich. On the other hand, studies in tropical montane forests in Venezuela, Jamaica and Hawaii have found relations of tree occurrence and growth with nitrogen (Tanner et al., 1998). Work on tropical montane forests is more advanced than that in lowland forests, as some montane forest work includes manipulative experiments rather than relying exclusively on correlation. Tanner et al. (1998) speculate that many lowland forests are limited by P and many montane forests by N.

6.) Zinc

Zinc deficiency can be caused by fixation by crystalline sesquioxides (Bennema, 1977: 36). Since sesquioxides (Fe_2O_3 and Al_2O_3) are the hallmark of latosols (Oxisols), zinc deficiency may pose a problem for plant growth. Zinc solubility bears a negative exponential relation to pH (pH values represent an exponent), and increases rapidly at soil pH values below 5 (Coelho and Verlengia, 1972: 58). Critical values for zinc in agriculture are between 1 and 2 ppm when extracted with 1 N HCl (Cox, 1973a: 183).

7.) Manganese

Manganese is a micronutrient required in small quantities by plants (Young, 1976: 291). However, at high levels it is toxic and, like aluminum toxicity, can inhibit plant growth. The availability of Mg to plants is closely tied to pH, with highest solubility at low pH. Manganese toxicity is a common problem for legume production in Brazilian agriculture on acid soils (Cox, 1973a: 87).

8.) Other elements

The above discussion has been restricted to elements believed to be potentially limiting for forest growth and for agriculture and ranching implanted on soils like those in the BDFFP reserves. The data set for the BDFFP reserve soils includes information on sulfur and copper. Boron, molybdenum and chloride were not analyzed. Total potassium was not analyzed: this measure is ordinarily not correlated with plant uptake and thus is primarily just of academic interest (Cox, 1973b: 162).

II.) THE BDFFP SOILS SURVEY

A.) OVERVIEW OF THE DATA SET

The soils data set contains surface samples from 1693 locations under forest in the BDFFP reserves (272 of which have additional samples taken at later dates), plus 41 soil profiles and 1693 soil density cores. This allows the effects of "fine scale" variation to be investigated in a way that would not be possible at the scale of soil maps used for zoning and other planning exercises, such as those based on the RADAMBRASIL surveys. The BDFFP soils data indicate substantial variability within an area that is all mapped as having identical soil on the RADAMBRASIL maps. The differences among sampling locations in the BDFFP reserves are sufficient to have an impact on agriculture were these areas (or areas like them) cleared and planted. The differences are also likely to affect the distribution of tree species within the forest, the biomass of the forest, and the susceptibility of the forest to drought stress if exposed to climatic variability (such as that provoked by the El Niño phenomenon), to the effects of edge formation through fragmentation and to the effects of probable climatic changes such as global warming and reduced rainfall due to loss of evapotranspiration.

B.) FIELD METHODS

Surface samples (0-20 cm) were taken using a screw-type soil auger, each sample being a composite of 15 cores taken at haphazardly chosen locations within a 20 m X 20 m quadrat. Quadrats were delimited by permanent markers at the corners (PVC pipes with numbered aluminum tags), thereby allowing the same locations to be resampled in additional studies.

A soil density sample was taken at the center of each quadrat where surface samples were taken. Volumetric cylinders were used 20 cm in length and 6.9 cm in diameter. The cylinder fits into the end of a soil corer on the shaft of which a movable weight slides up and down. The weight was raised and dropped repeatedly to pound the cylinder into the ground. Once in place, the cylinder was removed by digging around it with a digging tool, taking care that the cylinder is removed completely full of soil (which requires that the cylinder not be pulled out from above). The soil was removed by hitting the outside of the cylinder with a blunt instrument. Samples were placed in double plastic bags for transport to the laboratory and weighing.

A profile to 1.5-m depth was taken at the center of a subset of the quadrats using a "Dutch"-type soil auger. Each profile was divided into eight layers, the first seven samples corresponding to layers 20-cm thick (to a total of 1.4 m) and the last sample representing a 10-cm layer. The samples were laid out on a plastic tarp beside the hole to allow identification of horizons (by color, texture and plasticity). These descriptions follow the methods of Vieira and Vieira (1983: 60-81). The samples were then placed in separate plastic bags for transport to the laboratory. The sites of the profiles were identified by PVC pipes with numbered aluminum tags.

C.) LABORATORY METHODS

1.) Sample preparation, soil color, textural appearance and consistency

When surface and profile samples arrived from the field they were classified in the wet state for color (using a Munsell color chart), wet consistency (stickiness and plasticity), and textural appearance. These descriptions followed the methods of Vieira and Vieira (1983: 60-81).

The samples were then dried in a solar dryer, followed by 24 hours in an electric oven at 105^{0}C. After this drying, charcoal fragments were removed by hand, weighed and stored. The dry sample was then ground by hand (using a board and rolling pin), passed through a 20-mm and then a 2-mm mesh sieve. Stones and lateritic concretions removed in the sieves were weighed and recorded. A 300-g subsample of the dried soil was stored in a glass container in the voucher collection ("soloteca"). Additional 300-g subsamples were prepared for the INPA (National Institute for Research in the Amazon, Manaus, Amazonas) and CENA (Center for Nuclear Energy in Agriculture, Piracicaba, São Paulo) soils laboratories. Analyses of granulometric characters, bulk density, organic carbon, available water capacity and pH in H_2O and KCl were done at INPA; total N, total C, Al^{3+}, H^+, Ca^{2+}, Mg^{2+}, K^+, PO_4^{3-}, Cu, Fe, Zn, Mn were done at CENA. The INPA soil texture results were checked by comparison of 10 blind samples that were also analyzed by the EMBRAPA soils laboratory in Manaus; no significant differences were encountered. The CENA laboratory sends 10 samples every two months to one of a group of cooperating Brazilian laboratories to obtain an independent check on its chemical analyses.

2.) Soil texture

Textural (granulometric) analysis separated material into four fractions: coarse sand (grains 0.2-2.0 mm diameter), fine sand (grains 0.05-0.2 mm diameter), silt (particles 0.002-0.05 mm diameter) and clay (particles < 0.002 mm diameter) (Vieira and Vieira, 1983: 68). The particle size limits in these classes observe the United States Department of Agriculture standards, rather than those of the International Society of Soil Science. The pipette method was used (Brazil, SNLCS-EMBRAPA, 1979).

The clay fraction was determined by mixing soil in NaOH solution in an electric agitator. The mixture was then placed in a 1-liter sedimentation cylinder (graduated cylinder), mixed by successive inversions, and allowed to settle. After a period of time determined from a table depending on the temperature (e.g., 3 hours and 33 minutes for 25^{o}C) a 25-ml sample is drawn at a depth of 5 cm, using a pipette. The material was placed in a tared container, dried in an electric oven at 105^{o}C, and weighed.

Total sand (coarse + fine) was determined by sieving with a 0.053-mm mesh, followed by washing, oven drying and weighing the material. This material was then sieved in a 0.2-mm mesh sieve. The fine sand was weighed and the coarse sand determined by difference from the total sand. Silt was determined by difference of the total sample weight from the sum of the other three fractions.

3.) Bulk density

The samples were dried to constant weight in an electric oven at 105°C. Fine roots and charcoal were removed from these samples immediately after dry weight determination. Roots were then washed, oven dried, and weighed. Charcoal was stored after weighing.

4.) Organic carbon and organic matter

The modified Walkley-Black method was used at INPA, in which volumetric measurements are made by potassium bichromate and titration with ferrous sulfate. The method (Walkley and Black, 1934) included the modifications employed by EMBRAPA (Brazil, SNLCS-EMBRAPA, 1979). Organic matter was derived by multiplying the result by the constant 1.72 (Brazil, SNLCS-EMBRAPA, 1979), a common practice (Young, 1976: 102). The C/N ratio is organic carbon (Walkley-Black) divided by total nitrogen.

5.) Available water capacity

Field capacity and wilting point were determined indirectly on a pressure membrane apparatus (Soil Moisture Equipment Co., Santa Barbara, California), field capacity corresponding to moisture content under a suction of 0.33 atmospheres (bars) and wilting point to the corresponding value at 15 atmospheres. The difference in the amount of water held by the soil between these two points is the available water capacity. Moisture content and available water capacity are expressed as percent water by weight on a dry basis (Klar, 1984: 71). Note that, following the standard procedure, the soil was dried and sieved before being placed in the pressure plate rings, thereby altering its structure.

6.) pH in water and KCl

Soil reaction (pH) in distilled H_2O and in 1-N KCl solution were measured using a pH meter. The ratio of oven-dried soil to water or KCl solution is 1:1 on a volumetric basis (20 ml soil in 20 ml of water or solution). Work in tropical soils elsewhere has found soil reaction to increase by about 0.3 pH units in dried samples as compared to field conditions; pH is unaffected by storage once dried (Gillman and Murtha, 1983).

7.) Macro and micronutrients

The CENA methodology for micronutrient determination has been described by Zagatto et al. (1981) and Jorgensen (1977). Samples were digested using the EMBRAPA methodology: 0.0025 N HCl and 0.005 N H_2SO_4 (SNLS-EMBRAPA, 1979). K^+ was measured by atomic emission spectrophotometry in an air-acetylene flame, using a Perkin-Elmer AAS 306; Al^{3+}, Ca^{2+}, Cu, Fe, Mg^{2+}, Mn^{2+}, Na^+ and Zn^+ by atomic absorption spectrometry with plasma induced in argon, using a computerized spectrometer system (Jarell-Ash Plasma Atomcomp Direct Reading Spectrometer), and S (as barium sulphate) by turbidimetry, using a flow injection system. PO_4^{3-} was determined in an autoanalyzer using the molybdenum blue method (Jorgensen, 1977: 10).

8.) Total nitrogen

Total nitrogen was determined with Kjeldahl digestion, using a mixture of H_2O_2, Li_2SO_4 and concentrated H_2SO_4 to break down the organic matter and transform the nitrogen in the sample into NH_4^+ (Parkinson and Allen, 1975). The distillate was titrated with H_2SO_4.

9.) Total carbon (%C)

Total carbon (%C) was determined at CENA by the "dry" method, which converts the forms of soil carbon into CO_2 by combustion at 1100°C. The gas was then sent to a standard sodium chloride cell, where the difference in electrical conductivity between this solution and one carbonated with CO_2 was detected, and the result is expressed in milligrams of carbon (Cerri et al., 1990).

D.) SUMMARY OF RESULTS

Results presented here are restricted to the 54 non-contiguous ha in which tree surveys were carried out in the BDFFP project. The reserve area lacks patches of the best Amazonian soil types (anthropogenic black soil "terra preta do índio" and Alfisol "terra roxa estruturada"), and of the worst types such as white sand campina soils (podzols or Spodosols). Nevertheless, the data indicate a substantial variation in soil quality despite its uniformity at the level of general soil maps. Table 1 presents descriptive statistics on the hectare-level means.

[Table 1 here]

Clay content (mean value = 54.7%) varies greatly from 18.0-68.8%; since clay content is closely tied to several indicators of soil fertility, the general fertility level also varies substantially. The mean soil would be classed in the middle of the "clay" category (Vieira and Vieira, 1983: 68). The soil has a significant percentage of silt-sized particles (mean value = 21.2%), making the soil differ from some Amazonian soils where particles are concentrated in sand and clay fractions, with very little in between. However, it is possible that incomplete dispersion of clay aggregation could result in an apparent abundance of silt-sized particles when, in fact, this size class is present in much smaller amounts (Thierry Desjardins, personal communication, 1998). The statistical analyses were therefore performed lumping the clay and silt categories.

The terrain is undulating, with a mean slope of 10.8%. A portion of the area with steep slopes would be prone to erosion problems, in addition to not being appropriate for mechanized agriculture. Land-use capability classifications consider slopes of 0-2% to be without limitations, 2-8% to be slightly limited, 8-30% to be moderately limited, and >30% to be very limited (Benites, 1994: 215). By these criteria, of the 373 points with slope measurements in the data set used in the current study, 57.1% had no limitation, 23.6% had slight limitation, 23.1% had moderate limitation, and 2.7% had severe limitation from slope. In addition, the clay/sand content ratio of 2.6 (or 3.1, considering clay+silt) in the BDFFP reserves is considered an impediment to mechanization, the maximum value of this ratio considered appropriate being 2.0 (Vieira and Vieira, 1983: 123). However, this classification of mechanization limitations based on clay content represents an average for all of Brazil; W. Sombroek (personal communication, 1998) believes that yellow latosols in Amazonia, such as those in the BDFFP reserves, soils with higher clay contents could be mechanized.

The soil is quite acid, with a mean pH in water of 4.0 (range 3.4-4.4). However, it should be remembered that what is of interest to agriculture is not the level of nutrients in the soil under forest, but rather the level that will be present when the forest is cleared and burned. Especially in the case of pH, the values are increased by an amount that varies with burn quality (Fearnside, 1986b).

The delta pH (mean value = -0.3) indicates a net negative charge (a cation exchange capacity). This also confirms a reasonable level for soil organic matter by the standards of tropical agricultural soils.

Aluminum saturation (excluding H^+), with a mean value of 92.4%, is clearly high, while base saturation (without Na^+) is low, with a mean value of only 7.6%. Al saturation (without H^+) < 50% is classified as low and > 50% is classified as high (Vieira and Vieira, 1983: 144).

Total carbon had a mean value of 1.96%. Organic carbon, as determined by the modified Walkley-Black method, had a mean value of 1.58%. Organic matter had a mean value of 2.72%. While these values may appear low for agricultural soils, they are typical of Amazonia.

Total N levels are moderate, with a mean value of 0.16%; values less than 0.1% are considered "low" with a probable response to fertilization in crop plants, while values in the 0.1-0.2% are in the "moderate" range where responses are possible (Young, 1976: 291). The C/N ratio (mean value = 9.9) indicates a reasonable, but not ideal, quantity of nitrogen available to plants (values over 15 indicate little N in available forms).

Phosphate levels are very low (mean value of PO_4^{3-}=0.030 m.e./100 g of dry soil). PO_4^{3-} is considered "insufficient" for crop plants with levels <0.097 m.e./100 g of dry soil (equivalent to <2.30 m.e. of P_2O_5/100 g of dry soil); "fair" levels of PO_4^{3-} are 0.097-0.253 m.e./100 g of dry soil (equivalent to 2.30-6.00 m.e. of P_2O_5/100 g of dry soil), while "good" soil has >0.253 m.e. of PO_4^{3-}/100 g of dry soil (>6.00 m.e. of P_2O_5/100 g of dry soil) (Vieira and Vieira, 1983: 144)

Exchangeable potassium (K^+) is low, with a mean value of 0.06 m.e./100 g of soil; values below 0.2 m.e./100 g of dry soil are considered to be low, with fertilizer response probable in crop plants (Young, 1976: 291). A land-use capability rating system used in Brazil (Vieira and Vieira, 1983: 144) classifies K^+ levels < 0.11 m.e./100 g of dry soil as "insufficient," 0.11-0.37 as "fair" and > 0.37 as "good." The absolute minimum level required by crop plants is considered to be 0.10 m.e./100 g of dry soil (Boyer, 1972: 102). Of the nutrient cations, potassium is the one which is in greatest demand by crops (Webster and Wilson, 1980: 74). Lack of exchangeable potassium may therefore affect plant growth on these soils.

Calcium ion concentrations are very low (mean value = 0.058 m.e./100 g of dry soil). For crops, < 1.50 m.e./100 g of dry soil is "insufficient," 1.50-3.50 m.e./100 g of dry soil is "fair," and > 3.50 m.e./100 g of dry soil is "good" (Vieira and Vieira, 1983: 144).

Magnesium ion concentrations are fair (mean value = 0.076 m.e./100 g of dry soil. For crops, < 0.50 m.e./100 g of dry soil is "insufficient," 0.50-1.00 m.e./100 g of dry soil is "fair" and > 1.00 m.e./100 g of dry soil is "good" (Vieira and Vieira, 1983: 144).

The cation exchange capacity (expressed as the CEC of clay) is very low, with a mean value of 14.4 m.e./100 g of clay after correction for carbon. With a correction for carbon (each 1% of carbon is considered to correspond to 4.5 m.e. of CEC), a CEC of 24 m.e./100 g of clay is the dividing line between "low" and "high" activity clay (Vieira and Vieira, 1983: 38). The value of 24 m.e./100 g of clay is considered low for agriculture (Benites, 1994: 231).

Base saturation >50% is considered as indicating high fertility, provided that CEC of the clay is > 24 m.e./100 g of clay; base saturation < 50% indicates moderate fertility like these (Benites, 1994: 215; see also Vieira and Vieira, 1983: 46). The mean value of 7.6% (without Na^{+}) in the study area is obviously low, as is the maximum value of 12.2%. The Na^{+} levels found appear to be unusually high (mean = 0.052 m.e./100 g dry soil); combined with very low values for Ca^{2+} (mean = 0.058 m.e./100 g dry soil), Na^{+} makes an unusually large contribution to exchangeable bases. However, due to the much less complete data set for Na^{+}, cation measures excluding sodium were used in the statistical analyses.

The relationships among soil characters in the BDFFP data set are summarized in Table 2 for total exchangeable bases, organic matter, aluminum ions and available water capacity. Some of the other relationships shown in Figure 1, although known to hold generally, did not emerge as significant regressions in the BDFFP data set. Total exchangeable bases was not predicted significantly better by including pH (or $\log_{10}$ pH) in the regression, although higher pH values are known to be associated with greater amounts of cations such as Ca^{2+} and Mg^{2+} (see Fearnside, 1986). Phosphate was not significantly related to pH, Al^{3+} and Fe in the data set.

[Table 2 here]

III.) LESSONS FOR DEVELOPMENT

A.) AGRICULTURAL POTENTIAL

Our knowledge of the BDFFP reserve area greatly exceeds the level of knowledge that can be expected to be available for zoning decisions in the rest of Amazonia. If we can't come up with well-founded recommendations for this area, then we can't expect such suggestions to be obtainable for the vast majority of the rest of the region.

Wide differences of opinion exist as to whether a given fertility level means that an area should be opened up for agriculture, or that it should be maintained under forest cover. The data make clear that soil fertility is low and impediments to agriculture, such as aluminum toxicity, are substantial. This suite of problems leads some authors to conclude that soils such as these should not be used for agriculture. Irion (1978: 519), for example, concludes for soils on the Barreiras [or Alter do Chão] formation, such as those of the BDFFP reserves, "extensive cultivation .... is impossible, as the quality of the soil is insufficient. Any such cultivation, aiming at export of agricultural products, would result in an impoverishment of the soil within a few years, thus making the soil agriculturally unusable for many decades." Van Wambeke (1978: 233) warns of the potential for "irreversible destruction of soils and the creation of fertility deserts." On the other hand, Serrão and Homma (1993: 287), look at the same situation and conclude that 70% of the land in Brazilian Amazonia is "appropriate for crop production," and assert that "regions with low fertility and acidic soils have not been transformed into deserts, as some have foreseen.... On the contrary, such regions have been very dynamic in terms of agricultural development" (Serrão and Homma, 1993: 288). Whether these regions can be described as "very dynamic" is open to question; certainly the cattle ranches on which the BDFFP reserves are located are less-than-dynamic.

Amazonia in general, and particularly the state of Amazonas, has been protected from deforestation by impediments that include poor soils, human diseases (particularly malaria), and difficulty of access from densely populated portions of Brazil. But disease is no longer the barrier that it once was; for example, if opening areas today required the sacrifice of lives that opening the Madeira-Mamoré railway in Rondônia did at the beginning of the 20th century, then the threat of deforestation would be much less. Poor access is also rapidly changing: many settlers have gone directly from Rondônia to Roraima, bypassing the state of Amazonas through which they passed, a phenomenon explained both by somewhat better soils on the Guianan Shield in Roraima and by inducements offered by the government of Roraima. The paving of the BR-319 Highway linking Rondônia with Manaus, expected in 1998 or 1999, will open the flood gates to an influx of prospective settlers to central Amazonia, including the general area of the BDFFP reserves.

What happens when an area like the BDFFP reserves is cleared depends on what is done with the land. Some options are better than others from the standpoints of maximizing sustainability and minimizing environmental impact. Agroforestry, for example, is better in many respects than either annual crops or cattle pasture. However, severe limitations exist for widespread use of agroforestry in the vast areas of degraded lands that have already been created in the Amazon region, let alone the even larger areas that would exist if more forest were to be cut in the belief that agroforestry can solve the problems of sustaining production to support the human population (Fearnside, 1998).

The political discourse surrounding the announcement of new settlements in Amazonia is invariably permeated with images of permanent prosperity emanating from the agricultural systems to be implanted in the cleared areas. However, governmental decisions to cut the forest and implant agricultural settlements in areas with soils like those of the BDFFP reserves, which are typical of vast expanses of Amazonia, imply one of two things: either the government must be willing to provide or subsidize regular inputs of fertilizers for the indefinite future (a highly improbable scenario), or the decision-maker must accept responsibility for trading the forest for a landscape of degraded cattle pastures and second growth stands. Unfortunately, this responsibility is frequently avoided by recourse to histrionic devices such as the platitude that agriculture or ranching will be sustainable with "adequate management," the implication being that, if the project fails at some future date, then it will be the farmers who are to blame for not having applied "adequate management."

Two of the principal crops that are currently in fashion for promotion in Amazonia are not likely to be successful in areas like the BDFFP reserves. One is oil palm (e.g., Smith et al., 1995). In areas with a significant dry season (such as the Manaus area) the yield of oil drops quickly in comparison with optimal yields. In Brazilian Amazonia the two locations with optimal climatic conditions for oil palm are the area near Belém (Pará) and Tefé (Amazonas). Plantations in the Belém area suffer the effects of shoot rot disease (Fearnside, 1990). Because most of the costs of establishing and maintaining plantations are similar on a per-area basis regardless of the yield, plantations located in suboptimal areas are unlikely to be competitive.

The other crop that figures heavily in current discourse on Amazonian development is soybeans. Unfortunately, the social benefits from this crop are small for the local population, and the mechanized agriculture it requires is capital and chemical intensive. Although mechanization in areas like the BDFFP reserves is not impossible, the area would be less-than-ideal for these methods due to undulating terrain and high clay content of the soil.

Low soil fertility can be compensated by application of fertilizers. However, a series of severe constraints limits the extent to which agriculture based on a supply of nutrients from fertilizers can be extended to wide areas in Amazonia. The best example of this is the history of the "Yurimaguas technology" developed for continuous cultivation in Amazonian Peru (Sánchez et al., 1982; see Fearnside, 1987, 1988; Walker et al., 1987). Despite a long list of subsidies ranging from chemical inputs to free soil analyses and technical advice on a field-by-field basis, this high-input management package did not gain popular acceptance in the area. The limits of physical resources, such a phosphate deposits, as well as financial and institutional restraints, make widespread use of such systems unlikely (see Fearnside, 1997a).

Application of fertilizers is only one means by which soil fertility limitations can be addressed. One must consider the extent to which the agricultural prospects of areas like the BDFFP reserves would change if other kinds of technical advances were to occur. For example, recent progress has been made on removing aluminum saturation limitations through development of transgenic crop plants (Barinaga, 1997; de la Fuente et al., 1997). It is not inconceivable that phosphorus limitations could be relaxed by development of crop plants with appropriate micorrhizal associations. Nitrogen limitations of various non-leguminous crops may be relaxed through pseudosymbiotic relationships with a variety of types of nitrogen-fixing bacteria, an area in which significant advances have been achieved in Brazil through the work of Johanna Döbereiner (e.g., Döbereiner, 1992).

Today, however, it is not viable to sustain agriculture and ranching in vast areas of Amazonia due to limits of markets, phosphate deposits, and funds. Therefore one should not count on a "technological fix" to solve the problems of sustainability until such time as the technological advances in question are actually achieved. Not "counting one's chickens before they hatch" is a universal precautionary principle that is a basic rule for avoiding unwise adventures in myriad situations in addition to this one. One should also remember that the environmental costs of forest loss must be considered, and that these costs do not change much if the agriculture implanted is productive or not (see Fearnside, 1997a).

The soils in the BDFFP reserves are clearly infertile: indicators of soil fertility such as pH, cation exchange capacity, total exchangeable bases and PO_4^{3-} are low, while aluminum saturation is high. Under such circumstances, it is logical to maintain these areas under forest rather than converting them to short-lived low-productivity land uses. But to what extent would the situation be different if the soils were more productive? What level of soil quality would make it worthwhile to sacrifice the forest? There are no simple answers to these questions. Rational decision-making will require assessment of the value of both the agricultural production that can realistically be expected from the area and the environmental cost of sacrificing the forest.

So what is the lesson? These researchers are of the opinion that the main lesson is that the returns from converting areas like the BDFFP reserves to agriculture or ranching are minimal when compared the true value of the environmental services of the intact forest. Even though the amount that countries like Brazil may one day be able to collect on the basis of supplying these services is much less than the true value of the services, the returns from agriculture and ranching are also meager when compared with the amounts that might, in fact, be collected (Fearnside, 1997c; see Chapter ____[Laurance]).

B.) PROSPECTS FOR RESILIENCE

The relationships found among the various soil characters follow patterns that are consistent with what is generally known about tropical soils. These relationships (Figure 1 and Table 2) give an indication of some of the changes that are likely to occur in the face of human interventions such as selective logging, formation of edges through forest fragmentation, and removal of forest for implanting agriculture and ranching.

In the case of logging, changes normally found include soil compaction along logging tractor paths (Veríssimo et al., 1992). Nutrients are exported in the biomass removed (Ferraz et al., 1997), and soil cations are lost through leaching and runoff (Jonkers and Schmidt, 1984).

Outright removal of the forest has major impacts on soil nutrients and structure (see review in Fearnside, 1986b). Soil characters important for plant growth can be expected to change together: as they adjust to a new equilibrium they will tend to maintain the same relationships among each other that were found in the forest soil. Burning raises pH and provides inputs of nutrients to the soil, but cultivation usually leads to losses of organic matter and clay that gradually reduce the ability of the soil to hold cations. Some of the changes, such as loss of organic matter content and increase in soil compaction, can be reversed through periods under fallow. How much this capability for recovery of the soil, as well as capability for recovery of the forest, compensate for the impacts of deforestation is an important area of debate. Unfortunately, the theoretical possibility of recovery if areas are abandoned for many decades or even centuries has little relevance to the real impacts that are caused by the continued advance of deforestation in the region.

"Resilience" is a term that is fashionable in discussions of Amazonian development, and refers to the ability of a system to recover its original characteristics if perturbed (e.g., Smith et al., 1995). Are the soils of the BDFFP reserves likely to be "resilient" if they are converted to pasture and degraded? Reasons to doubt this include the already low levels of key elements that would be further depleted. Among the changes that normally occur are loss of clay and carbon, together with the cations that are tied to these components. Carbon can be regenerated under extended fallows, but, in practice, it is doubtful that fallows would be left for sufficient periods for this to happen (Fearnside, 1996a).

Different people can look at the same set of facts and arrive at radically different conclusions. Serrão et al. (1996: 8), for example, take the regrowth of secondary forest in abandoned pastures to indicate that "the Amazonian upland forest ecosystem is fairly resilient to current uses," whereas others would disagree (e.g., Fearnside and Guimarães, 1996).

C.) DISTRIBUTION OF NATURAL VEGETATION

On a broad scale, a relationship between soil and tree species and biomass is evident, such as the difference between campina and campinarana vegetation with low biomass that grows on white sand soils in the Manaus area, versus the upland forests with high biomass on more clayey soils like those in the BDFFP reserves. Within more similar soils, such as those in the reserve system, differences are more subtle but are likely to be present.

Studies in various parts of the tropics indicate relationships between tree species occurrence and soils. In a review by Sollins (1998) of 18 studies in tropical lowland forests, relations between species occurrence and soil drainage regimes were common. Notable is the study by Lescure and Boulet (1985) of 16.8 ha of forest in French Guiana, which found that 69% of the tree species showed response to soil drainage conditions.

Only three of the 18 studies reviewed by Sollins (1998) were able to detect relationships of tree species occurrence to chemical properties: Ashton and Hall (1992) found relationships with P and cations in Sarawak and Brunei; Clark et al. (1995) found relationships with P, Al and pH in Costa Rica, and Van Schaik and Mirmanto (1985) found a relationship with pH in Sumatra. The three studies that reported relationships with chemical properties were those with the largest ranges of values for the chemical indicators of fertility (the independent variables). Sollins (1998) believes that the limited range of soil fertility within the areas in which studies have been attempted to relate species occurrence to chemical properties is a primary reason for the elusiveness of demonstrating significant relationships. Other confounding factors include seasonal variation in some key fertility indicators, especially available phosphorus, cations and pH. Both of these restrictions apply to the BDFFP data set as well.

Soil fertility and water relations can be expected to be related to seedling survival and to the growth rates of trees. Species associations with soils may be related to forest biomass if species characterized by larger individuals are found on certain soils. Any soils effect on the occurrence of species that become large canopy emergents would have a great effect on biomass because a large part of forest biomass is often held in only a few very large individual trees (Brown et al., 1995; Clark and Clark, 1985). Independent of species effects, general favorability of the soil for plant growth can be expected to be positively associated with forest biomass. An ordination analysis relating biomass to soils in the BDFFP reserves indicates that 53% of the variation in biomass is explained by a gradient in clay content (and positively associated levels of total N, organic C, exchangeable bases, K^+, Mg^{2+}, Ca^{2+}, Al^{3+}, H^+ and CEC)(Laurance et al., 1999).

D.) POTENTIAL FOR RELEASE OF GREENHOUSE GASES

Carbon stocks in soil and in forest biomass in Amazonia are very large due to high per-hectare loading and to the vast areas of Amazonian forest still standing. Release of these stocks is a significant contributor to global warming at present rates of deforestation (Fearnside, 1996b, 1997d), while the large remaining stocks mean that the potential future importance of avoiding emission is even greater (Fearnside, 1997c). Converting each hectare of forest to the equilibrium landscape that replaces it releases approximately 8.5 t of soil carbon to the atmosphere considering soil to 8-m depth over 15 years, or 7.4 t C/ha to a depth of 1 m (Fearnside and Barbosa, 1998).

The fine-scale spatial variability in soil carbon distribution indicated by the BDFFP soil survey suggests a substantial amount of uncertainty is inherent in studies of soil carbon change based on "chronosequences," where the effects of land uses (such as pasture) are inferred from comparison of roughly simultaneous samples taken at a series of sites with different land-use histories (see Fearnside and Barbosa, 1998). Substantial differences among these sites could be due to natural spatial variation, rather than to the effect of land use.

E.) PROBABLE RESPONSE OF FOREST TO FRAGMENTATION

The BDFFP has provided undeniable evidence that creation of edges results in greatly increased mortality of trees located near the edges (Laurance et al., 1998; Lovejoy et al., 1984). These edges have drier air than the forest interior (Kapos, 1989; Kapos et al., 1993). Tree mortality near the edges leads to a "biomass collapse," releasing carbon to the atmosphere (Laurance et al., 1997).

Soils are likely to play a role in mortality of trees under these conditions. Soils with greater amounts of sand can be expected to retain less water, leading to greater drought stress when conditions are dry due to edge proximity. However, sandy soils are associated with valley bottoms, which would be expected to have some additional water as compared to higher locations.

F.) PROBABLE RESPONSE OF FOREST TO CLIMATIC CHANGE

Climatic variations and changes of several types exist or are predicted. The El Niño-Southern Oscillation event, a periodically recurring phenomenon which is not caused by human action, results in droughts that can have significant impact on Amazonian forest. Tree species that are specialized on wetter sites are particularly vulnerable to drought stress. For example, such species in the forest on Barro Colorado Island, Panama, suffered extraordinarily high mortality during the 1982-1983 El Niño event (Hubbell and Foster, 1990: 531).

Archeological evidence suggests that catastrophic fires have occurred in Amazonia at the times of major El Niño events four times over the past 2000 years: 1500, 1000, 700 and 400 B.P. (Meggers, 1994). Human action could now turn less-intense El Niño events, such as the 1982-1983 and 1997-1998 events, into major catastrophes. Such less-intense events are much more frequent than major ones, but these would be added to the effects expected from climatic changes such as reduction in rainfall from lowered evapotranspiration caused by continued deforestation (Salati and Vose, 1984) and the effect of temperature and rainfall changes caused by global warming (see Fearnside, 1995). While neither of these changes is expected to result in radical reductions in rainfall, the effect is added to that of natural variability such as that caused by El Niño events and disturbances such as logging and edge formation. Logging is rapidly increasing in Amazonian forests, leading to more flammable conditions from accumulation of slash and accidentally killed trees in the logged-over forests (Uhl and Buschbacher, 1985; Uhl and Kauffman, 1990). The continued advance of settlement and deforestation in the region means that many more opportunities exist than in the past for fires to enter adjacent forests. These effects are added to those of climate variability and climatic change, increasing the risk of fire entering standing forest.

Soils play a role in the forest's response to these events. As in the case of edge-related drought stress, trees on soils with little available water are more likely to succumb to extreme events.

IV.) CONCLUSION

The soils of the BDFFP reserves are typical of vast areas of Brazilian Amazonia that are likely to come under increasing pressure for deforestation. These soils have low fertility, are acid and have high levels of toxic aluminum ions. They also have limitations from rolling topography, high clay content, and low available water capacity. The soils data indicate that they would produce little if converted to agriculture or ranching, and point to land uses that maintain forest cover intact as preferable. Although the value of the environmental services provided by standing forest currently provides no source of cash income, the potential value of these services far exceeds the returns that can be expected from cutting the forest for agriculture or ranching.

V.) NOTES

[1] The defining criterion for latosols is that the B horizon must be "latosolic," as opposed to "textural" (i.e., clayey). The criterion for identifying "latosolic" character in the Brazilian soil classification system is that the ratio of silicon and aluminum oxides (SiO_2:Al_2O_3) must have a value less than two (see Sombroek, 1966: 69). Values below two generally indicate that the silicate clay minerals have a 1:1 lattice structure (Sombroek, 1966: 80). The ratio refers to the number of sheets of silica tetrahedra to sheets of alumina octahedra, and is one of the primary determinants of the properties of the clay (Young, 1976: 73). The lower amount of silicate in these soils, as compared to those with a 2:1 lattice structure, is a consequence of removal of silicon from the soil column (along with most weatherable minerals, including important nutrients for plants) over millions of years of leaching. In the absence of analytical data on SiO_2 and Al_2O_3, clay mineralogy of subsoil horizons (which are low in organic matter) can be deduced from the cation exchange capacity (CEC) of the clay fraction, which is calculated as the CEC of the soil divided by the percent clay, multiplied by 100; values below a cutoff point of 16-20 m.e./100 g clay indicate absence of 2:1 lattice minerals (Young, 1976: 95-96).

[2] The pH of the extracts used in laboratory analyses affects the values obtained for the cations that make up the CEC and, since the determinations are not normally made at the natural pH of the original soil, the values only represent an index of the true CEC. In Brazil, the extracts used for the determinations are buffered to pH 7.0 (Brazil, SNLCS-EMBRAPA, 1979). Values for CEC determined at the pH of the soil (effective CEC) are much lower than those determined either at pH 7.0 or at the pH 8.2 standard sometimes used in the United States (Sánchez, 1976: 150-151).

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FIGURE LEGEND

LIST OF TABLES

TABLE 1: VARIATION IN SOIL PROPERTIES IN THE BDFFP RESERVES (0-20 cm)

(descriptive statistics of site means)

Category	Soil character	Units	Mean	SD	Minimum	Maximum	N
GRANULOMETRIC CHARACTERS							
	Clay	%	54.7	13.5	18.0	68.8	54
	Silt	%	21.2	4.3	8.3	32.5	54

	Fine sand	%	5.6	3.9	1.3	18.1	54
	Coarse sand	%	18.5	12.5	4.4	56.6	54
AVAILABLE WATER							
	Soil moisture content @ 1/3 bar	% H2O by weight	31.8	6.8	13.0	41.2	45
	Soil moisture content @ 15 bars	% H2O by weight	24.3	5.8	9.1	31.9	45
	Available water capacity	% H2O by weight	7.6	2.0	3.3	12.0	45
TOPOGRAPHY							
	Slope	%	10.8	8.9	1.4	38.7	36
CARBON							
	Organic matter	%	2.1	0.7	0.8	3.3	50
	Organic C (Walkley Black)	%	1.6	0.3	0.8	2.2	40
	Total C	%	1.96	0.45	1.27	3.07	51
	C/N ratio	dimensionless	9.9	1.6	8.4	17.0	38
	C stock to 20 cm	t/ha					
SOIL REACTION							
	pH in H2O	pH units	4.0	0.3	3.4	4.4	53
	pH in KCl	pH units	3.8	0.2	3.2	4.3	53
	Delta pH	pH units	-0.3	0.1	-0.5	0.0	53
PRIMARY NUTRIENTS							
	N (total)	%	0.16	0.03	0.10	0.21	3

							8
	PO43-	m.e./100 g dry soil	0.030	0.005	0.022	0.041	38
	K+	m.e./100 g dry soil	0.060	0.011	0.032	0.077	38
SECONDARY NUTRIENTS							
	Ca2+	m.e./100 g dry soil	0.058	0.026	0.015	0.131	38
	Mg2+	m.e./100 g dry soil	0.076	0.031	0.013	0.125	38
	Na+	m.e./100 g dry soil	0.052	0.018	0.026	0.106	18
	S	ppm	13.0	1.4	10.6	15.0	13
MICRONUTRIENTS							
	Cu	ppm	0.33	0.12	0.10	0.54	24
	Fe	ppm	137	31	77	185	24
	Zn	ppm	1.48	0.78	0.61	2.99	24
	Mn	ppm	1.81	0.49	0.87	2.49	24
OTHER IONS							
	Al3+	m.e./100 g dry soil	1.63	0.29	1.03	2.22	38
	Al sat. w/ H+, w/ Na+	% of CEC	89.4	1.0	86.3	90.5	18
	Al sat. w/ H+, w/o Na+	% of CEC-Na+	92.4	1.7	87.8	96.2	38
	Al sat. w/o H+, w/ Na+	% of Base sat.+Al3+	85.2	1.2	82.4	86.5	18
	Al sat. w/o H+, w/o Na+	% of Base sat.+Al3+	89.5	2.2	84.3	94.4	38
	H+	m.e./100 g dry soil	0.70	0.12	0.39	0.85	38
CATION MEASURES							
	Cation	m.e./100 g	2.7	0.2	2.5	3.0	1

exchange capacity (w/ Na+)	dry soil					8
Cation exchange capacity (w/o Na+)	m.e./100 g dry soil	2.5	0.4	1.7	3.3	3 8
CEC of clay (w/o Na+)	m.e./100 g dry clay	5.1	1.6	3.7	10.5	3 8
CEC of clay (w/o Na+) w/ C correction	m.e./100 g dry clay	14.4	1.7	10.9	18.2	3 8
Total exchangeab le bases (w/ Na+)	m.e./100 g dry soil	0.3	0.0	0.2	0.4	1 8
Total exchangeab le bases (w/o Na+)	m.e./100 g dry soil	0.2	0.1	0.1	0.3	3 8
Base saturation (w/ Na+)	% of CEC	10.6	1.0	9.5	13.7	1 8
Base saturation (w/o Na+)	% of CEC	7.6	1.7	3.8	12.2	3 8

TABLE 2: RELATIONSHIPS AMONG SOIL PARAMETERS

TOTAL EXCHANGEABLE BASES (without Na^+):

$$TEB = 1.86 \times 10^{-3}\ CS + 3.88 \times 10^{-2}\ OM - 5.20 \times 10^{-2}$$

($p < 0.00001$, $r^2=0.84$, $n=38$)

where: TEB = Total exchangeable bases (without Na^+) (m.e./100g dry soil)
CS = Clay + silt (%)
OM = Organic matter (%)

ORGANIC MATTER

$$OM = 2.13 \times 10^{-2}\ CS + 1.12$$

($p < 0.00001$, $r^2=0.73$, $n=38$)[a]

where: OM = Organic matter (%)
CS = Clay + silt (%)

ALUMINUM IONS

$$Al^{3+} = 7.66 \times 10^{-3}\ CS - 7.70 \times 10^{-1} \log_{10} pH + 5.64$$

($p < 000001$, $r^2=0.78$, $n=38$)

where: Al^{3+} = Al^{3+} (m.e./100g dry soil)
CS = Clay + silt (%)
pH = pH in water (pH units)

AVAILABLE WATER CAPACITY

$$AWC = 5.24 \times 10^{-2}\ CS + 3.66$$

($p < 0.01$, $r^2 = 0.43$, $n=45$)

where: AWC = Available water capacity (% H_2O by weight)
CS = Clay + silt (%)

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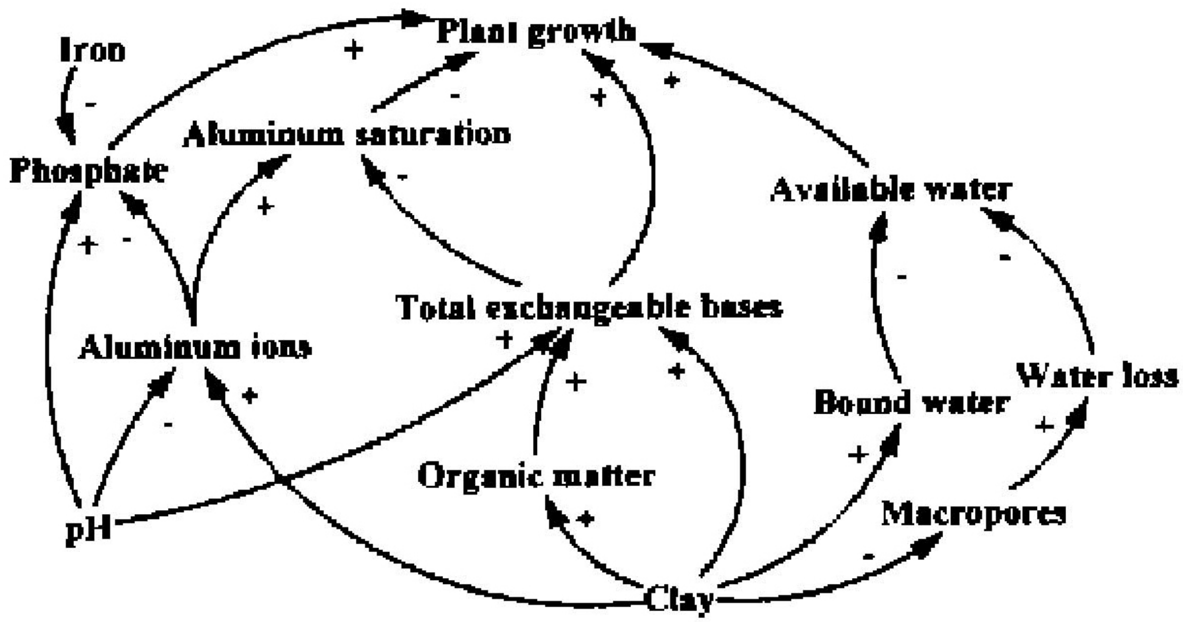
a.) With elimination of one outlier.

Fig. 1


Plant growth
Iron
Aluminum saturation
Phosphate
Available water
Total exchangeable bases
Aluminum ions
Water loss
Bound water
Organic matter
pH
Macropores
Clay