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Phosphorus and Human Carrying Capacity in Brazilian Amazonia

Philip M. Fearnside

National Institute for Research in the Amazon (INPA), C.P. 478, 69011-970 Manaus, Amazonas, Brazil

HUMAN CARRYING CAPACITY

The term "carrying capacity" has been used by workers in biology, anthropology, geography, range management, fisheries, wildlife management, and business management with related but different meanings. All refer to the number of individuals that can be supported in a given area; the level of consumption at which they are to be supported and the length of time the area is to be capable of providing this support varies with the definition. The term sometimes has been used to refer to an *instantaneous* relationship between available resources and the consumption requirements of a population, as in the logistic equation of population biology (e.g., Wilson and Bossert, 1971). In this paper, however, the term is used exclusively with reference to sustainable levels of population and consumption. Carrying capacity in the present case refers to the number of people that can be supported for an indefinite period, given assumptions concerning production technology and the population's levels and patterns of consumption.

Carrying capacity is not fixed, but neither is it infinitely expandable (Arrow et al., 1995; Cohen, 1995). Carrying capacity can be increased through changes in the ways resources are used and distributed; it can also decline through environmental degradation, through increasing inequality in the distribution of resources, and through adoption of inefficient land-use patterns like cattle pasture, all of which are occurring in Amazonia today.

Roger Revelle (1976) calculated that the earth could support 40 billion people, assuming large increases in per-hectare yields and use of all land that he thought available (including Amazonia). Revelle's assumptions regarding high-input agriculture in Amazonia are at variance with a number of known limitations in the region (see Revelle, 1987). The Food and Agriculture Organization of the United Nations (FAO) suggested in 1971 that the earth could support 36 billion people if uncultivated areas, including Amazonia, were converted to United States–level agriculture (Pawley, 1971).

The predominant feature of development in Brazilian Amazonia (Fig. 1) so far has been conversion of forest to cattle pasture (Fearnside, 1990b). Cattle pasture is a land use that causes maximum impact on forest while supporting only a very sparse human population (Fearnside, 1983). New initiatives may alter this scenario in significant ways. Soybeans are being promoted by the national and state governments; the first major plantations are in natural grasslands near Humaitá, Amazonas. The Madeira River waterway, opened in March 1997, lowers the cost of transport from this part of the region to one-third of its former cost, thus radically altering the economic picture for more intensive agriculture there. A 90,000-t warehouse has been established in Itacoatiara, Amazonas, at the mouth of the Madeira River, and a second such warehouse is expected in a subsequent phase. Soybeans already represent an important crop in northern Mato Grosso and eastern Rondônia. Expansion in Roraima is planned. Little employment results from soybean cultivation, which is conducted using mechanized agriculture.

Figure 1. Brazil's Legal Amazon region.

Land-use decisions based on permitting the maximum intensity that physical conditions will allow can quickly exceed limits in other spheres when individual allocations are considered together. One may examine each cell in a grid in a geographical information system, comparing soil, rainfall, etc., with the given crop demands, and conclude that each individual cell can be allocated to the use in question, and yet arrive at a global conclusion that is patently unrealistic.

The FAO, in collaboration with the United Nations Fund for Population Activities (UNFPA) and the International Institute for Applied Systems Analysis (IIASA), estimated carrying capacity in Amazonia and other tropical areas of the world (FAO, 1980, 1981, 1984; Higgins et al., 1982). It is worthwhile examining the FAO/UNFPA/IIASA study in some detail, as the illusion implied in it that Amazonia can be turned into a major breadbasket—an idea that long predates the FAO/UNFPA/IIASA study—is a persistent and pernicious one in Brazilian Amazonian planning. The study's results contain numerous conclusions that are glaringly inconsistent with reality, indicating that such efforts need to be based on on-site research. Brazilian Amazonia is all mapped in the FAO/UNFPA/IIASA study as capable of supporting between one-half and one person hectare^{-1} at the present low-input level of technology, and between five and 10 people hectare^{-1} with high inputs (fertilizers, mechanization, and an optimal mix of rain-fed crops). These calculations lead to the conclusion that Brazil could support an incredible 7.1 billion people, were high-level inputs applied (Higgins et al., 1982). The implied possibility of converting the region to high-input mechanized agriculture runs up against limits of resources, especially of phosphates.

One factor leading to the high carrying-capacity values the FAO/UNFPA/IIASA study ascribed to Amazonia is the assumption that land quality in uncultivated areas is equal to that in already cultivated ones. The study goes so far as to claim that "there is evidence that the productivity of the reserves may be higher, but, for the sake of simplicity, it is assumed that the potential productivity of the unused land is the same as that of the land under cultivation" (FAO, 1984). Unfortunately, as is true in most parts of the planet, the best land is brought into cultivation first, with land quality declining progressively in new settlement areas until only very marginal lands remain.

In the early 1970's, when the fiscal incentives program for Amazonian pastures was rapidly expanding, the Brazilian Enterprise for Agriculture and Cattle Ranching Research (EMBRAPA) maintained that pasture improved the soil. Falesi (1974) compared soils under virgin forest and pasture of various ages on the Belém-Brasília Highway at Paragominas in Pará and at the Suiá-Missu Ranch in northern Mato Grosso:

> Immediately after burning [of forest] the acidity is neutralized, with a change in pH from four to over six and Al disappearing. This situation persists in the various ages of pastures, with the oldest pasture being 15 years old, located in Paragominas. Nutrients such as calcium, magnesium, and potassium rise in the

chemical composition of the soil, and remain stable over the years. Nitrogen falls immediately after the burn but in a few years returns to a level similar to that existing under primitive forest... The formation of pastures on latosols and podzolics of low fertility is a rational and economic manner in which to occupy and increase the value of these extensive areas. (Falesi, 1974: 2.14–2.15)

Phosphorus was not among soil characters indicated as improving as a result of pasture in EMBRAPA's original publications (Falesi, 1974, 1976), but was added to the list by others when the results were made public (e.g., Alvim, 1981). EMBRAPA itself recognized that P was necessary, and in 1977 changed its position that pasture improves soil, recommending instead that productivity be maintained by applying 200 to 300 kg ha^{-1} of phosphate fertilizer (50% simple superphosphate, 50% hyperphosphate; Serrão and Falesi, 1977) to supply 50 kg ha^{-1} P_2O_5 (Serrão et al., 1978: 28). This amount was subsequently modified to 25 to 50 kg ha^{-1} P_2O_5 (Serrão et al., 1979), but more recent recommendations have called for the original 50 kg ha^{-1} (Correa and Reichardt, 1995).

While the pasture soil controversy may appear to be a past misunderstanding that can be consigned safely to the dustbin of history, its ramifications are still a force in Amazonian development to this day. The notion that pasture was improving soil was coincident with the launching of a massive program of fiscal incentives to promote conversion of forest to pasture. Tax incentives were a strong motive for deforestation in the 1970's and 1980's. On June 25, 1991, a decree suspended the granting of new incentives. However, the old (i.e., already approved) incentives continue still, contrary to popular impression fostered by numerous statements by government officials to the effect that incentives had been ended. The more than 400 already approved ranching projects outweigh the small number of additional projects that would be added to the list each year had new project approvals continued.

The soil changes noted by Falesi (1974, 1976) do not lead to the conclusion that pastures will be sustainable (Fearnside, 1980). High pasture-grass yields cannot be sustained if growth is being restricted by low quantities of certain nutrients, such as P, regardless of the quantities of other nutrients. Using data from pasture fertilization experiments in Belém (Serrão et al., 1971), lack of P can be shown to limit pasture-grass growth (see Fearnside, 1979). Low P has also been found to limit grass growth in Paragominas (Serrão et al., 1978, 1979). The data from Falesi's Belém-Brasília Highway study (1974, 1976) show a strong downward trend in available P after an initial peak from burning virgin forest. Available P (P_2O_5) falls from a high of 4.18 mg 100 g^{-1} dry soil in new pasture to a lower plateau after five years. The five-year-old pasture has a P_2O_5 content of 0.46 mg 100 g^{-1}, and after some slight variation the value is still 0.46 mg 100 g^{-1} in the 10th year (Falesi, 1976), lower than virgin forest soil at 0.69 mg 100 g^{-1}.

Much debate regarding soil changes under pasture is irrelevant to the question of maintaining pasture productivity. The question of importance is, are the low values to which P levels fall under pasture adequate to sustain production? The answer is no, as poor yields confirm, both in experimental and commercial plantings wherever fertilizers are not applied.

Problems limiting reliance on phosphate fertilizers are the cost of supplying phosphate and the absolute limits to minable stocks of this mineral. A report on Brazil's phosphate deposits published by the Ministry of Mines and Energy indicates that only one small deposit exists in Amazonia (actually, two close together: Serra Pirocua and Ilha Trauira), located on the Atlantic coast near the border of Pará and Maranhão (de Lima, 1976; see also Fenster and León, 1978; Fig. 2). In addition to its small size, the deposit has the disadvantage of being made

Figure 2. Phosphate deposits in Brazil.

up of Al compounds that render its agricultural use suboptimal, but not impossible if new technologies were developed for fertilizer manufacture (dos Santos, 1981). An additional deposit has been found on the Maecuru River, near Monte Alegre, Pará (Beisiegel and de Souza, 1986), but estimation of its size is still incomplete. Almost all of Brazil's phosphates are in Minas Gerais, a site very distant from most of Amazonia.

Brazil as a whole is not blessed with a particularly large stock of phosphates; the United States, for example, has deposits about 20 times larger (de Lima, 1976). Brazil's reserves constitute only 1.6% of the global total (de Lima, 1976). Continuation of post–World War II trends in phosphate use would exhaust the world's stocks by the middle of the 21st century (United States CEQ and Department of State, 1980). Although simple extrapolation of these trends is questionable because of limits to continued human population increase at past rates, the conversion of a substantial portion of Amazonia to fertilized pasture would greatly accelerate the exhaustion of phosphate stocks in Brazil and the world. Brazil would be wise to ponder carefully whether its remaining supply of this limited resource should be allocated to Amazonian pastures.

A rough calculation can be made of the adequacy of Brazilian phosphate reserves to sustain pastures in Amazonia. Brazilian reserves of phosphate rock total 780.6×10^6 t, with an average P_2O_5 content of 12% (de Lima, 1976), not counting the Maecuru deposit still being assessed. Discounting loss of 8% of P_2O_5 in transforming rock to phosphate fertilizer (de Lima, 1976), this represents 86.2 $\times 10^6$ t of P_2O_5. The 53.0×10^6 ha of forest cleared by 1997 in the Legal Amazon (INPE, 1998) would consume 1.06×10^6 t of P_2O_5 annually if maintained in pasture. This assumes that pastures are fertilized once every 2.5 years (Serrão et al., 1979), at the 50 kg ha^{-1} dose of P_2O_5 per fertilization, considering a minimum critical level of 5 $\mu g\ g^{-1}$ P_2O_5 in the soil rather than the traditional critical level of 10 $\mu g\ g^{-1}$, which would require annual doses of fertilizer to maintain. If the entire 400×10^6 ha of originally forested area in the Legal Amazon were fertilized at the rate recommended for pasture, it would require 8.00×10^6 t of P_2O_5 annually. If all of Brazil's phosphate reserves were devoted to this purpose, they would last 81 years maintaining the currently deforested area (an area the size of France) under pasture, and only 11 years if the remainder of the originally forested area were also converted to pasture. However, Brazil's fertilizer deposits are already almost totally committed to maintaining agricultural production outside the Legal Amazon.

PHOSPHATES AS A LIMITING FACTOR

Agriculture

Phosphorus is low in virtually all soils in Brazilian Amazonia, even including relatively fertile ones such as *terra roxa* (Alfisol) occurrences in settlement areas along parts of the Transamazon Highway in Pará and the BR-364 Highway in Rondônia. On the Transamazon Highway west of Altamira, a 23,600-ha study area mapped from 187 virgin forest samples had 83% of the land with less than 1 μg g^{-1} available P in the top 20 cm of soil, and 91% with total P less than or equal to 2 μg g^{-1}, as determined using the North Carolina extractant that is standard for available P determinations in Brazil (Fearnside, 1984).

A variety of soil characteristics and processes determine available P present. Phosphorus availability in Ultisols is generally very low because most P is in highly insoluble Fe and Al compounds (Kamprath, 1973). Values of pH below 5.5 are generally associated with marked decrease in P availability (Young, 1976; see review in Jordan, 1985). Organic C and Fe_2O_3 both are positively related to available P in Brazilian Oxisols (Bennema, 1977). Mycorrhizae are important in mobilizing P into available forms (St. John, 1985). Mycorrhizal associations have been found in many but by no means all of the few Amazonian trees that have been examined (St. John, 1980).

When P is in available forms, the process of fixation converts it to unavailable complexes with Fe and Al. Oxisols in Amazonia are not generally considered to be high-P fixers (Cochrane and Sánchez, 1982). Phosphorus fixation depends on soil characters: organic matter counteracts P fixation, while low pH favors it (Bennema, 1977). Phosphorus fixation rates (in 6 h at 100 μg g^{-1} P) range from 26.8% to 51.6% in representative soils of the Brazilian Amazon (Fassbender, 1969). These rates are not high by the standards of many tropical Oxisols and Ultisols, but more P is lost to fixation at low (and more probable) fertilizer application rates. In *terra roxa* (Alfisol) in Altamira, Pará, the best upland soil type in the region aside from very small patches of anthropogenic black soil, up to 83% of P applied is fixed in 7 d at low (53 μg g^{-1} P) application rates (Dynia et al., 1977). Aluminum toxicity itself acts partly through P, as Al tends to accumulate in roots and impedes uptake and translocation of both P and Ca to aerial portions of the plant (Sánchez, 1976).

Forest Management

The poor prospects of sustaining large areas of pasture is one reason that forest management for timber is often suggested as the best use for large areas of forest. Daunting economic barriers stand in the way of keeping forest under sustainable management systems over a succession of cycles (Fearnside, 1989). One must also consider whether P might pose an additional limit.

Nitrogen has often been assumed to limit forest growth. For example, in a model developed by the Biomass and Nutrients project for INPA's "Model Basin" near Manaus, N was assumed to be limiting for the forest as a whole (Biot et al., 1997). Such an assumption is probably a consequence of lack of literature on other nutrients, and indicates need for research to quantify links of other soil characters to forest growth.

Leguminous trees are able to fix N with the aid of symbiotic bacteria, which probably gives members of this superfamily a competitive advantage over species in families that lack this capability, and helps explain why legumes are a common group in Amazonian forests. However, legumes are hardly a dominant feature of

Amazonian forests; for example, in the reserves maintained near Manaus by INPA/Smithsonian Institution Biological Dynamics of Forest Fragments Project, Burseraceae, Sapotaceae, and Lecythidaceae are all more common than legumes (Rankin-de-Merona et al., 1990). While N is undoubtedly important, it cannot be assumed to be controlling forest growth.

Amazonian forests apparently receive a significant part of their P supply from African dust transported across the Atlantic Ocean by winds (Swap et al., 1992). The amount of dust is increased by overgrazing and other land-use and land-management changes in Africa, and by a climate characterized by increasingly severe drought events. Nutrients are also contributed by smoke and ash particles from burning in savannas, possibly including those in Africa (Talbot et al., 1990). The extent to which these nutrient sources could increase growth of Amazonian forests is not known. Increases undoubtedly differ by tree species, thereby potentially altering forest composition (Fearnside, 1995).

Environmental Role of the Forest

Amazonian forest is of significant value in ways other than by providing timber or in making way for agricultural or ranching expansion. This forest provides environmental services, for which no one pays anything at present, that far outweigh the financial return from traditional commodities. These services include biodiversity maintenance, C storage (avoidance of global warming), and water cycling. With proper negotiation and institutional mechanisms, tapping the value of these services could provide a sustainable basis of support for the present rural population in Brazilian Amazonia (Fearnside, 1997a).

If P limits biomass growth in the forest, then this element may have a place in the environmental role of the forest, particularly for C storage. One controversy regarding global warming is the extent to which CO_2 fertilization from higher atmospheric concentrations of this gas might result in C absorption by the forest by stimulating biomass accumulation. Whether this occurs hinges on other limiting factors that restrain forest growth. Medina and Cuevas (1996) have argued that the effect of higher concentrations of CO_2 in increasing the efficiency of water and nutrient use would result in increased forest growth, especially during the dry season. These authors argue that much of the increased photosynthate is allocated to roots and root exudates, which could in the long run help relax soil-nutrient limitations on growth. If P were limiting growth during any period of the year, for example during the rainy season when other limitations are relaxed, then this element would have a role in the global C balance. Phosphorus would also have an influence on Amazonia's role in the global C balance if P limits secondary forest growth in degraded cattle pastures (Fearnside and Guimarães, 1996).

LESSONS OF PHOSPHATE LIMITATIONS

Given that phosphates represent a limiting factor to long-term sustainability of agriculture and ranching activities in Amazonia, what lessons should we draw from this? What would be limiting if infinite supplies of phosphates were to become available, or if a wonder crop were discovered that required virtually no P? It has been argued that the environmental impact of converting a large portion of Amazonia to agriculture or ranching would (or should) lead Brazilian decision-makers to take steps to avoid such a transformation, even if such improbable developments were to materialize (Fearnside, 1997c). The primary lesson of limited P is not that more plant physiology research is needed, but that we need to learn to live within this and other limits.

When confronted with the existence of a limiting factor, the normal reaction on the part of both decision-makers and researchers is to concentrate efforts on finding ways to overcome the limitation. The question of whether or not the limit should be pushed back in the first place is normally not even considered. However, this basic question must be answered before any effort to overcome a limitation can make sense. Once a decision has been reached that limits must be pushed back to some extent, then it is necessary to obtain information on the full range of factors that limit attainment of defined developmental objectives. The reflexive reaction that all limiting factors must be overcome is both wasteful and unwise. Once relevant information is organized and interpreted, the effectiveness, cost, and social and environmental side-effects of attacking the different limits can be compared.

A common reaction is to view as a given the current highly unequal distribution of land tenure and to concentrate attention only on technical advances against soil restraints. I would suggest that soil and related physical conditions are much more "given" than are restraints that result from the country's social and decision-making hierarchy, and that the latter category is where attention should be focused. What are the ingredients of a rational decision regarding whether or not to attempt to overcome a limitation on development? The starting point must be a clear definition of the objectives of development. For example, if the objective of development is to provide a sustainable livelihood for the populations of the region, then little benefit will be achieved by augmenting productivity or life expectancy of cattle pastures by supplying fertilizers and improving management. Many efforts to push back limits to crop production have as their rationale supporting an ever-larger population of farmers, for example, of immigrants who come to Amazonia from other parts of Brazil. This is not necessarily in the best interests of Amazonia's current population and their descendants. It would be better to recognize that the ability of Amazonia to support population is limited, and to guide development in such a way that population size and environmental impacts are kept within those limits (Fearnside, 1997b).

There is no such thing as sustainable development for an infinite number of people, nor for a fixed population that is infinitely rapacious. Many physical limits represent restrictions that need to be respected and lived with rather than attacked. Recognition of this fact forces one to face fundamental problems of development that many people would prefer not to think about—resulting in a tendency to deny the existence of limits. Admitting the finite potential for growth of the "pie" does not condemn the poor to poverty, but rather condemns the rich to dividing the pie (Fearnside, 1993).

FUTURE RESEARCH PRIORITIES

The temptation is always strong to believe that research will remove virtually all limits to development, and nowhere are such flights of imagination more free to run wild than in Amazonia. It is easy for planners to convince themselves that crop yields can increase indefinitely, and can increase at ever-increasing rates. Recently, Gallopín and Winograd (1995) arrived at an optimistic conclusion regarding prospects for a "sustainable scenario" by assuming that per-hectare yields of crops will increase exponentially at 1.5% to 2.0% per year. The idea that exponential growth is an option is misleading, and the notion that one can select it as if picking something off a shelf is even more dangerous. In reality, Brazilian per-hectare yields traditionally have been almost constant, increases in total harvest coming instead from expansion of areas under cultivation (Paiva et al., 1976).

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

The soils in Amazonia are clearly infertile: indicators of soil fertility such as pH, cation-exchange capacity, total exchangeable bases, and available P are low, while Al 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 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 realistically can be expected from the area and the environmental cost of sacrificing the forest.

"We need more research" is not the primary conclusion to be drawn from the foregoing review. While more research will indeed be important, the most urgent need is for actions based on our current knowledge. Even simple back-of-the-envelope calculations point to fundamental inconsistencies in the balance of population, consumption, and resources in Amazonia. Similarly crude calculations also indicate that returns from converting areas of Amazonian forest to not condemn the poor to poverty, but rather condemns the rich to dividing the pie (Fearnside, 1993).

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"We need more research" is not the primary conclusion to be drawn from the foregoing review. While more research will indeed be important, the most urgent need is for actions based on our current knowledge. Even simple back-of-the-envelope calculations point to fundamental inconsistencies in the balance of population, consumption, and resources in Amazonia. Similarly crude calculations also indicate that returns from converting areas of Amazonian forest to agriculture or ranching are minimal when compared to the value of environmental services of intact forest. Even though the amount of money that countries like Brazil may one day be able to collect from supplying these services is much less than the true value of the services, returns from agriculture and ranching are also meager when compared with amounts that might actually be collected (Fearnside, 1997a). The lesson to be learned from phosphate limitations on intensification of agriculture and ranching in Amazonia is the need to face the finite nature of the potential for these activities, and adapt population and development policies accordingly.

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