PN-AAK-997

ICN: 13023

Project 931-0525
Contract AID/TA-C-1236

Amazon Basin Soils: Management for Continuous Crop Production

Pedro A. Sanchez, Dale E. Bandy
J. Hugo Villachica, John J. Nicholaides

Summary. Technology has been developed which permits continuous production of annual crops in some of the acid, infertile soils of the Amazon Basin. Studies in Yurimaguas, Peru, show that three grain crops can be produced annually with appropriate fertilizer inputs. Twenty-one crops have been harvested during the past 8½ years in the same field, with an average annual production of 7.8 tons of grain per hectare. Soil properties are improving with continuous cultivation. The technology has been validated by local farmers, who normally practice shifting cultivation. Economic interpretations indicate large increases in annual family farm income and a high return on the investment of chemical inputs. Other promising land use alternatives include low-input crop production systems, paddy rice production in fertile alluvial soils, and pastures or agroforestry in rolling areas. Stable, continuous food crop production is an attractive alternative to shifting cultivation in humid tropical regions experiencing severe demographic pressures. For each hectare of land managed in a highly productive manner, there may be less need for clearing additional tropical forests to meet food demands.

The humid tropics, which cover about 10 percent of the world's land surface, is a crucial ecosystem because of its agricultural potential and the possible ecological consequences of its deforestation (*1–4*). Projections of world food supply and demand indicate that an additional 200 million hectares must be put into cultivation before the turn of the century just to maintain the present, largely inadequate, level of food production in the developing world (*5*). This amount of land, which exceeds the harvested cropland in the United States, is needed despite the expected increase in yields in areas now under cultivation.

The use of high-yielding crop varieties, fertilization, and irrigation in fertile soils resulted in impressive increases in food production in the tropics during the 1970's (*6*). It is widely acknowledged that future efforts to increase world food production must be directed toward the marginal lands of the developing world, where, because of severe climatic and soil constraints, preservation of the land resource base is a major consideration (*7*).

Several land resource studies indicate that the greatest potential for agricultural expansion into virgin or underutilized lands lies in the humid tropics and acid savannas (*1, 8*). The humid tropics is that part of the world with a variation of less than 5°C in mean monthly air temperature between the three warmest and three coldest months, no more than a 4-month period in which potential evapotranspiration exceeds precipitation, and native forest vegetation. This ecological region occupies about 1500 million hectares, of which at least half is considered potentially arable or grazeable (*1, 8, 9*). The acid savannas are areas with a similar temperature regime, tropical savanna vegetation, a dry season of 4 to 6 months, and predominantly acid soils. They occupy about 300 million hectares, of which 150 million are potentially arable or grazeable (*9*).

Large-scale expansion of agricultural land in other ecosystems is hampered by low temperatures, lack of water, severe erosion, or already intensive land use. The humid tropics and acid savannas are blessed with temperatures, rainfall, and topography which favor agricultural development. The main factors limiting such development are low soil fertility, a limited transportation and marketing infrastructure, and lack of appropriate soil management technology. Agricultural development is progressing rapidly in those acid savanna regions where transportation and marketing are being improved and soil management technology is being applied (*10*). Ecologically, the acid savannas are considered less fragile than the humid tropics (*11*).

Estimates of the rate of conversion of tropical forests into agricultural land vary widely; so do estimates of the environmental consequences associated with such conversions (*3, 4, 12, 13*). Despite the divergence of opinion, one basic premise runs through many reports on this topic: that it is not possible to continuously cultivate the acid, infertile soils of the humid tropics. The red or yellowish color of most of these soils, indicative of the presence of iron oxides, has led to the generalization that when cleared and cultivated they will turn into laterite, a red desert, or a compacted soil surface resembling the Sahel (*12, 14*).

More than 50 years ago, C. F. Marbut, the father of American soil science, traveled in the Amazon region and published an article (*15*) stating that most of the soils he observed were strikingly similar to the main soils of southeastern United States. During the past decade, major soil mapping efforts and soil management research have confirmed Marbut's statements and provided a quantitative assessment of the properties and potential of soils in the Amazon Basin.

Soils of the Amazon Basin

Soil taxonomy is similar to plant taxonomy in the sense that only properties that can be measured are considered (*16*). The world's soils have been mapped with a common soil legend at a scale of 1:5 million (*17*). This legend is readily converted into soil taxonomy units. Detailed surveys have been conducted in parts of the humid tropics with satellite and radar imagery—particularly in the Amazon. This region has been mapped at a scale of 1:1 million. A synthesis of the land resources of tropical America is now available in computer-retrievable form from the International Center for Tropical Agriculture (CIAT) (*18*). This synthesis, together with other data, makes it possible to accurately characterize the soils of the Amazon region (*19*).

Some 75 percent of the Amazon Basin is dominated by acid, infertile soils classified as Oxisols and Ultisols (Table 1). They are deep, well-drained, red or yel-

The authors are all at the Department of Soil Science, North Carolina State University, Raleigh 27650.

0036-8075/82/0521-0821$01.00/0

Table 1. General distribution, by topography, of major soils in the Amazon Basin (19).

Soil grouping	Millions of hectares				
	Flat, poorly drained	Well-drained			Total (percent)
		Slope 0 to 8 percent	Slope 8 to 30 percent	Slope > 30 percent	
Acid, infertile soils (Oxisols and Ultisols)	43	207	88	23	361 (75)
Poorly drained alluvial soils (Aquepts, Aquents, Gleysols)	56	13	1		70 (14)
Moderately fertile, well-drained soils (Alfisols, Mollisols, Vertisols, Tropepts, Fluvents)	0	17	13	7	37 (8)
Very infertile, sandy soils (Spodosols, Psamments, Podzols)	10	5	1		16 (3)
Total	109	242	103	30	484

lowish soils with favorable physical properties, but they are very acid and deficient in plant nutrients (20). Next in abundance (14 percent) are the poorly drained alluvial soils, which are located mainly in flood plains or inland palm swamps. About 8 percent of the Amazon Basin has well-drained soils with moderate to high fertility. Although only 3 percent is covered by the extremely acid and infertile sandy soils known as Tropical Podzols, Spodosols, and Psamments, research on such soils has received widespread attention (21). Conclusions based on the extreme paucity of nutrients typical of these soils cannot be generalized to the entire Amazon.

About half of the Amazon Basin consists of well-drained landscapes with slopes of less than 8 percent (Table 1). The other half has poor drainage or slope limitations.

Most of the constraints imposed by Amazon soils on agricultural development are chemical, rather than physical, in nature (Table 2) (22). Phosphorus deficiency is found in 90 percent of the soils; the effects of this deficiency depend on which crops are grown. Fortunately, only 16 percent of the Amazon has soils capable of fixing large quantities of phosphorus into relatively insoluble forms. Although most Amazon soils will require phosphorous fertilization, the quantities required are not likely to be as high as in the acid savannas, where high phosphorus fixation is a major problem (10).

Aluminum toxicity, the main cause of poor plant growth in acid soils, affects about three-fourths of the region. Low potassium reserves are also widespread. Poor drainage and flooding affect one-fourth of the region (this area includes flood plains and inland swamps).

About 15 percent of the Amazon has effective cation exchange capacity (CEC) values below 4 milliequivalents per 100 grams. A low CEC indicates that there are few negative charges in the soil capable of retaining nutrient cations such as calcium, magnesium, and potassium. Consequently, even when large quantities of such nutrients are applied, they can be rapidly lost by leaching, particularly in well-drained soils. Also, since soils with low CEC values are poorly buffered, fertilizer and lime applications may affect the behavior of other soil properties.

About 92 percent of the Amazon has soils that are relatively secure from severe erosion. This is partly due to the level to gentle slopes found in 82 percent of the region (19) and partly to the favorable structure of many Oxisols and Ultisols. The highly erodible soils (39 million hectares) occur mainly on steep slopes. Such soils are susceptible to erosion unless protected by a plant canopy. Overall, the Amazon soils are less erodible than soils in other major ecological zones, such as the semiarid tropics.

This is not to imply that erosion is a trivial issue in the Amazon. All soils can be eroded through mismanagement, and sheet erosion can occur in nearly level, well-drained Oxisols and Ultisols if they are not protected by vegetation. This seldom happens in tropical forested regions, because when crops or pastures fail, weeds and secondary forest regrowth usually produce a plant canopy rapidly. Sheet erosion and gullying along cattle trails in poorly managed, overgrazed pastures, however, are increasing. Most of the obvious gully erosion involves roads, building sites, and urban sewage or drainage systems.

Only 4 percent of the Amazon is subject to laterite formation (Table 2). This percentage reflects the 21 million hectares of soils (Plinthaquox, Plinthaquults, and Plinthudults) with soft plinthite in the subsoil. This point deserves emphasis, given the widespread belief that Amazon soils, once cleared, are irreversibly transformed into hardened plinthite or laterite. These three soil groups are the only ones in which this phenomenon can occur, but because the soft plinthite is in the subsoil, the topsoil has to be removed by erosion before hardening to laterite can take place. Since these soils occur mainly on flat, poorly drained landscapes, erosion is not likely to be extensive.

Hardened laterite outcrops are found in geomorphically predictable positions in areas geologically affected by Guayanan and Brazilian shields, and sometimes are mixed with soil materials. They are in reality an asset to development because they provide excellent road-building materials at low cost. The lack of laterite in upper Amazon areas not affected by the Precambrian shields is a constraint to road building.

Only about 6 percent of the Amazon has soils with no major limitations to agriculture. Nevertheless, they represent a total of 32 million hectares. They are classified mainly as Alfisols, Mollisols, Vertisols, and well-drained alluvial soils, and where they occur permanent agriculture has a very good chance of success.

Need for Continuous Cultivation Technology

Although food crop production should logically concentrate first on the more fertile soils of a region, the limited extent of such soils in the Amazon and the considerable flooding hazard associated with many of them indicate that major increases in food crop production must be based on the dominant Oxisols and Ultisols. At present, shifting cultivation is almost the only food crop production system in Oxisol and Ultisol regions of the Amazon. Farmers slash and burn a patch of the forest and harvest one or two crops before soil fertility, derived almost entirely from the ash of the burned vegetation, is depleted and weed control problems force them to abandon the land. Although shifting cultivation in its traditional form is ecologically sound

(23), it is a guarantee of perpetual poverty for those who practice it (24). Increased population pressures in several parts of the Amazon have resulted in a shortening of the periods during which the land is left fallow, precluding restoration of the soil's fertility and turning an ecologically sound farming system into an unproductive, ecologically damaging one. This is already evident in much of the forested zone of West Africa, where a rapid increase in population density has led to the conversion of most of the virgin forest into highly unstable shifting agriculture (3, 25).

Table 2. Principal limitations of soils in the Amazon Basin under native vegetation (19).

Problem*	Million hectares	Percentage of Amazon Basin
Phosphorus deficiency	436	90
Aluminum toxicity	352	73
Low potassium reserves	271	56
Poor drainage, flooding	116	24
High phosphorus fixation	77	16
Low cation exchange capacity	71	15
High erodibility	39	8
No major limitations	32	6
Steep slopes (> 30 percent)	30	6
Laterite formation if subsoil exposed	21	4
Shallow (< 50 centimeters deep)	3	

*Nitrogen, sulfur, magnesium, and zinc deficiencies and temporary drought stress are widespread, but cannot be quantified with available data.

Research Program in Yurimaguas

In 1971 North Carolina State University, in cooperation with the predecessor agencies of the Instituto Nacional de Investigación y Promoción Agraria, initiated the Tropical Soils Research Program in Yurimaguas, Peru, to determine whether continuous cultivation of basic food crops is possible in acid, infertile soils of the Amazon Basin (26). Yurimaguas, the westernmost large fluvial port of the Amazon headwaters (5°45'S, 76°05'W; 184 meters above sea level) has a mean annual temperature of 26°C and mean annual rainfall of 2100 millimeters. The rainfall is well distributed throughout the year, with 3 months averaging 100 millimeters and the rest about 200 millimeters. The native vegetation is tropical rainforest. The principal soil of the experiment station is a flat, well-drained Ultisol, with a sandy loam surface over a clay loam subsoil. It is very acid (pH 4.0), high in aluminum, deficient in phosphorus, potassium, and most other nutrients, and low in CEC (26). These conditions are typical of much of the Amazon.

The choice of land clearing method is the first and probably the most crucial step affecting the productivity of farming in the humid tropics. Field trials confirmed that methods involving slash-and-burn are superior to mechanical removal of vegetation. The ash produced by burning adds nutrients to the soil, while bulldozing often causes soil compaction and displaces topsoil, depositing it outside the field (27).

After identifying the desirability of traditional slash-and-burn land clearing, researchers then focused on determining the most appropriate crops and crop rotations, fertilization needs and changes in soil properties with cultivation. Several basic food crops have been studied, including upland rice, corn, cassava, plantains, soybeans, peanuts, sweet potatoes, cowpeas, and winged beans, either as monocultures or in combinations (26). The most promising results so far have been obtained by growing three crops a year as rotations of upland rice, corn, and soybeans or upland rice, peanuts, and soybeans. These rotations are adapted to the rainfall pattern and keep the ground covered most of the year. Continuous monoculture of the same crops, however, did not produce sustained yields because of a buildup of pathogens.

Figure 1 shows the grain yields of 21 consecutive crops harvested from the same field since it was cleared by slash-and-burn in October 1972 and cultivated with the rice, corn, and soybean rotation. Without fertilization, yields dropped to zero after the third consecutive crop. With complete fertilization, the long-term average of this rotation, which was replicated in three fields, was 7.8 tons of grain per hectare per year.

The upland rice, peanut, and soybean rotation was also successful. It may be more appropriate because in this environment peanuts have a higher yield potential than corn. Corn suffered from

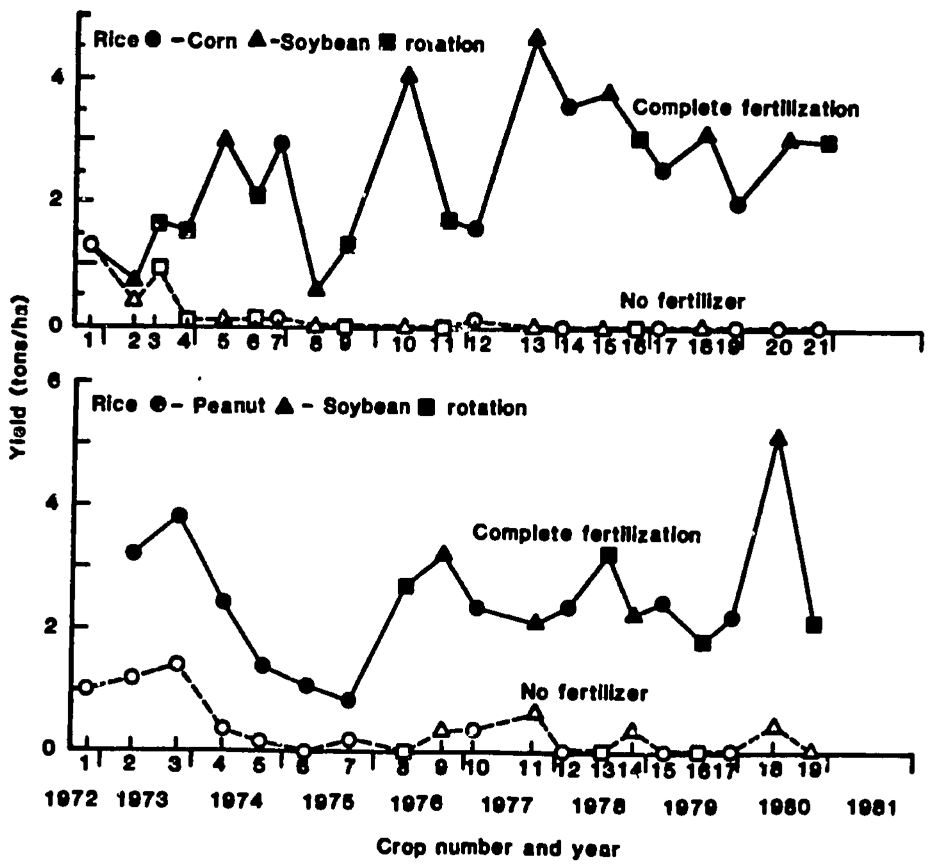


Fig. 1. Yield record for two continuously cultivated plots at Yurimaguas, with and without fertilization (26).

the low solar radiation and high night temperatures, and it was subjected to more insect attacks than the other three crops. Figure 2 shows the long-term average yields of 88 harvests of these four crops with and without adequate fertilization during the past 8 years. Upland rice, soybean, and peanut yields are excellent; corn yields are moderate. Figure 2 also indicates a reasonable yield stability for the four crops. These results show that continuous production can be achieved in the Amazon with adequate fertilization.

Nutrient Dynamics: The Key Factor

The term "adequate fertilization" was not arrived at lightly. It took about 4 years to gather conclusive data on the changes in soil properties that occurred after clearing and burning a 17-year-old secondary forest and growing annual crops continuously. The nutrient dynamics were monitored by sampling soils after each harvest and analyzing for *p*H, organic carbon, total nitrogen, exchangeable aluminum, potassium, calcium, magnesium, effective CEC, and available phosphorus, zinc, copper, iron, and manganese. Sulfur, boron, and molybdenum levels were determined periodically by plant analysis. Such records were kept for three fields cleared in 1972, 1973, and 1974. The fields were given complete, intermediate, or no fertilization, and there were four replications. The timing of the appearance of soil fertility limitations and the intensity of their expression varied among the fields, even though they were near each other, were on the same soil mapping unit, and had the same vegetation before clearing. The intensity of the fire during clearing is considered a factor contributing to this variability.

Table 3. Fertilizer requirements for continuous cultivation of annual rotations of rice, corn, and soybeans or rice, peanuts, and soybeans on an acid Ultisol in Yurimaguas (*26*).

Input*	Amount per hectare	Frequency
Lime	3 tons	Once every 3 years
Nitrogen	80 to 100 kilograms N	Corn and rice only
Phosphorus	25 kilograms P	Every crop
Potassium	80 to 100 kilograms K	Every crop, split application
Magnesium	25 kilograms Mg	Every crop (unless dolomitic lime is used)
Copper	1 kilogram Cu	Once a year or once every 2 years
Zinc	1 kilogram Zn	Once a year or once every 2 years
Boron	1 kilogram B	Once a year
Molybdenum	20 grams Mo	Mixed with legume seeds only

*Calcium and sulfur requirements are satisfied by lime, simple superphosphate, and magnesium, copper, and zinc carriers.

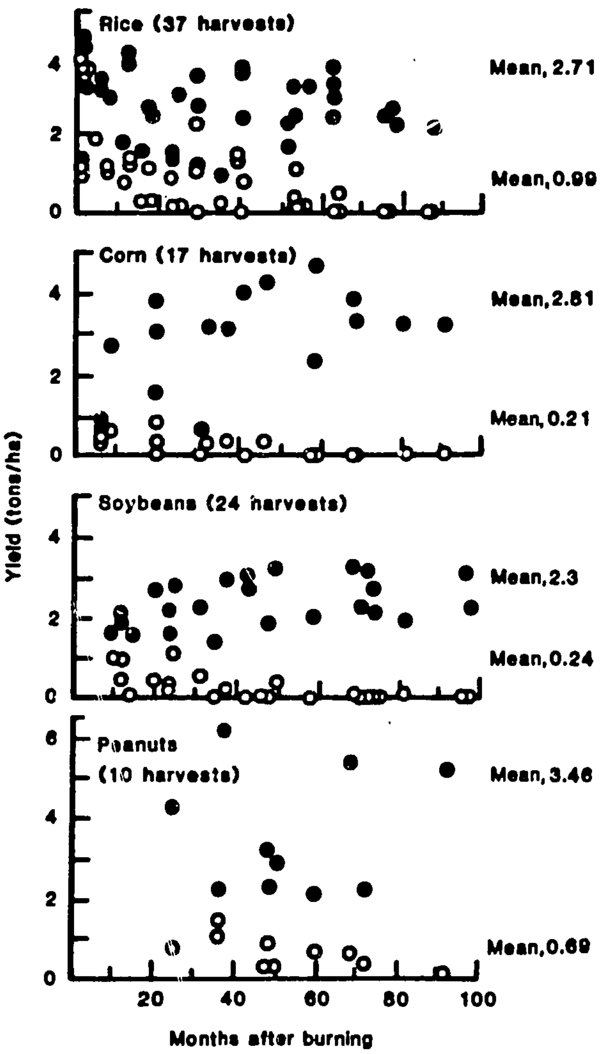


Fig. 2. Crop yields at Yurimaguas (1972 to 1980) with complete fertilization (●) and with no fertilization (O).

Ash from the burning produced a temporary increase in *p*H, available nitrogen, phosphorus, potassium, calcium, magnesium, and some micronutrients and a decrease in exchangeable aluminum to below toxic levels. As a result, upland rice, the first crop planted, did not suffer from soil fertility limitations. By about 8 months after clearing, however, the levels of available nitrogen and potassium were reduced such that crops were affected adversely; in addition, sporadic sulfur, copper, and boron deficiencies appeared. Organic matter in the topsoil decreased sharply during the first year, with a decomposition rate of 25 percent per year. Organic matter reached a new equilibrium level starting with the second year. The rapid organic matter decomposition probably released many H^+ ions that acidified the soil and increased exchangeable aluminum to toxic levels, reversing the liming effect of the ash.

Phosphorus and magnesium became deficient during the second year, calcium during the first 30 months, and zinc during the fourth year. Manganese deficiency is suspected after the eighth year. Molybdenum deficiencies were detected in soybeans, particularly when seed produced in acid soils of the Amazon Basin was used, but not when the seed came from more fertile soils of the Peruvian coast.

In the complete treatment, fertilizers and lime were added according to recommendations based on soil analysis. During the second or third year, however, all yields began to decline rapidly. Soil analysis identified two responsible factors: a shorter than expected residual effect of the lime applied, and the triggering of a magnesium deficiency induced by the potassium applications. After these problems were corrected, crop yields stabilized (Fig. 2). Thus, a monitoring of the nutrient dynamics during the period when the soil was undergoing a transi-

Table 4. Changes in topsoil (0 to 15 cm) properties at Yurimaguas after 8 years of continuous cultivation and 20 crops of upland rice, corn, and soybeans with complete fertilization (26).

Time	pH	Organic matter (%)	Exchangeable, milliequivalents per 100 square centimeters				CEC	Al saturation (%)	Available (parts per million)				
			Al	Ca	Mg	K			P	Zn	Cu	Mn	Fe
Before clearing	4.0	2.13	2.27	0.26	0.15	0.10	2.78	82	5	1.5*	0.9*	5.3*	650*
Ninety-four months after clearing	5.7	1.55	0.06	4.98	0.35	0.11	5.51	1	39	3.5	5.2	1.5	389

*Thirty months after clearing.

tion from forest to cropland provided the key for establishing continuous cultivation.

Table 3 presents lime and fertilizer recommendations developed during 8 years of research at Yurimaguas. Like all sound fertilizer recommendations, they are site-specific. Nevertheless, they are representative of the level of fertilizer input required for continuous crop production in Ultisols. These fertilizer levels do not differ substantially from those used to grow corn, soybeans, and peanuts in Ultisols of the southeastern United States. On an annual basis, the total amounts of fertilizer required are higher in the Amazon than in the Southeast because three crops are grown instead of one.

Effects of Continuous Cultivation on Soil Properties

It is a common belief that cultivation degrades soils in the humid tropics (12, 14). Our results, however, indicate that soil properties improve with continuous cultivation systems combining intensive management and appropriate fertilization. After 20 consecutive crop harvests at Yurimaguas, the topsoil pH increased from a very acid 4.0 before clearing to a favorable level of 5.7 (Table 4). Organic matter content decreased by 27 percent, but most of this loss occurred during the first year. Exchangeable aluminum decreased from very high levels to minimal amounts, exchangeable calcium increased 20-fold (a consequence of lime applications), and exchangeable magnesium doubled. Exchangeable potassium did not increase despite the application of large quantities of potassium fertilizer, suggesting rapid utilization by crops and perhaps losses due to leaching. Effective CEC doubled as a consequence of the pH-dependent charge characteristics of the kaolinite clay and iron oxides. Fertilization also increased available phosphorus from below the critical level of 10 parts per million to substantially above it. The same trend occurred with zinc and copper. Available manganese, however, decreased to levels approaching deficiency. Available iron remained considerably above the critical range of 20 to 40 parts per million. On the whole, these changes indicate improvement in the topsoil's chemical properties.

There have been no unfavorable changes in the soil's physical properties thus far because of the protection three well-fertilized crops per year provide against the rains (26). Although crop residues are left in the field until the experimental plots are tilled for the next planting, the soil is exposed for up to 30 days before a full crop canopy is reestablished. Occasional runoff losses have been observed, but they have not been of sufficient magnitude to affect yields.

Acid, infertile subsoils of Oxisols and Ultisols frequently act as chemical barriers to root development. Crop roots are unable to enter a subsoil highly saturated with aluminum ions and very low in exchangeable calcium (28). This produces shallow root systems, which often result in drought stress during rainless periods (the subsoil may still have plenty of water, but the plants cannot reach it). With time, however, continuous cultivation leads to an alleviation of this problem. We observed significant increases in calcium, magnesium, and effective CEC and a decrease in aluminum saturation in subsoil 15 to 45 centimeters deep (Fig. 3). Fertilization promotes the downward movement of these basic cations, which results in a more favorable environment for root development than before clearing.

Technology Validation in Farmer Fields

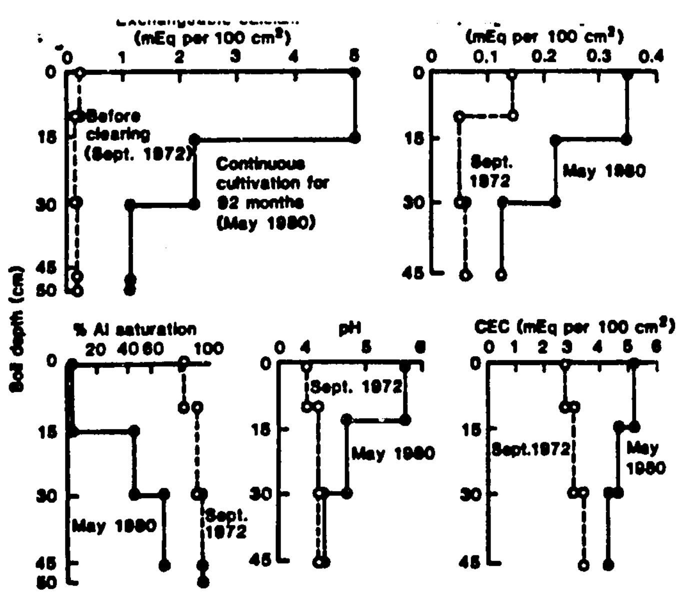
In 1979 a number of demonstration plots were established in shifting cultivators' fields within an 80-kilometer radius of Yurimaguas. Three crop rotations were tested. The complete fertilization schedule (Table 3) was implemented, as adjusted by on-site soil tests (29). The first eight farmers averaged 3 tons of rice per hectare, 4.5 tons of corn, 2.6 tons of soybeans, and 1.8 tons of peanuts—yields similar to those obtained at the station. The tests have expanded, and farmers are attracted by the prospect of increasing their yields six- to tenfold (their traditional average is 1 ton per hectare per year) while avoiding the need to clear new land every year.

Economic Implications

The combined results indicate that the continuous production system is economically viable over a wide range of crop and fertilizer prices, capital levels, and labor force compositions (30). When it was assumed that only the typical family was available for labor, that the farmer borrowed about U.S.$150 from the agrarian bank, and that fertilizers were bought at world market prices and transported overland from Lima, the annual family income increased four times, from the present average of $750 to about $3000 per 1.5 hectares. Also, for every additional dollar borrowed to buy fertilizer at a marginal cost of $0.18, profits ranged from $1.29 to $4.95 (30). Given the favorable response of the Peruvian government to what is now being called the Yurimaguas technology, the local availability of fertilizer and credit has increased and marketing facilities have improved. Several farmers are using the new system, but invariably they have planted larger areas than suggested by the economic analysis. To do so, they obtained outside labor or hand tractors. It is too soon to ascertain the performance of these pioneers.

Current Research Efforts

Continuous cultivation of annual food crops with appropriate fertilization is one of several options for sustained agriculture in the humid tropics. The Tropical Soils Research Program is developing technology for other land uses, with emphasis on intensive crop production in fertile alluvial soils, low-input crop pro-



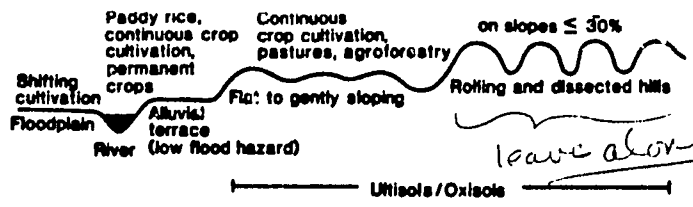


Fig. 3 (left). Improvement in chemical properties of the subsoil after 7½ years of continuous cultivation of a rotation of rice, corn, and soybeans at Yurimaguas (*25*). Fig. 4 (right). Rational land-use options for Amazon Basin landscapes. Wherever possible, regions of cultivated Oxisols and Ultisols should be surrounded by forest reserves in a mosaic pattern.

duction systems in Ultisols and Oxisols, and legume-based pastures and agroforestry for sloping Ultisols and Oxisols.

Relatively fertile alluvial soils that are not subject to flooding have a major food production potential. Improved rice varieties and spacing in alluvial soils can result in the doubling of upland rice yields without eliminating shifting cultivation (*31*). The rotations of three crops per year are producing excellent yields in such soils in field trials. The high *p*H and fertility of these soils eliminate the need for lime and decrease the fertilizer requirements. Research is in progress for developing paddy rice production technology with irrigation water pumped from rivers or wells.

Decreasing the level of fertilization is likely to increase economic returns in the well-drained Ultisols. Ongoing research in this direction includes minimum or zero tillage, utilization of indigenous rock phosphates, and improving the efficiency of fertilization, particularly that of potassium. Selection of varieties of upland rice, soybeans, peanuts, corn, cowpeas, sweet potatoes, and winged beans for tolerance to acid soil stresses is also in progress (*32*). Promising results are being obtained with rice and cowpeas. The inclusion of such tolerant germ plasm is expected to substantially decrease the lime and phosphorus requirements of continuous cultivation systems.

Organic inputs such as mulch, green manures, and compost have been studied as possible substitutes for chemical fertilizers. Mulching crops with residues from the previous crop or with *Panicum maximum* grass has produced unreliable results in over 20 experiments, with generally detrimental results for upland rice, some positive results for corn, and little effect on soybeans and peanuts (*33*). These results contrast with the positive results of such practices in Nigeria (*34*), where the most serious soil problems are physical rather than chemical in nature.

The use of kudzu (*Pueraria phaseoloides*) as a green manure has often resulted in crop yields similar to those following complete fertilization (*35*). The labor involved in harvesting, transporting, and incorporating kudzu into the soil, however, imposes severe practical limitations. Making compost out of crop residues appears more promising. For the first four consecutive crops, replacing complete fertilization with compost from crop residues resulted in only a 20 percent yield reduction (*36*). To sustain yields afterwards, it was necessary to apply potassium fertilizer with the compost. The use of this practice is restricted by the high labor requirements of compost making.

Research is also in progress on the use of managed kudzu fallows as an intermediate stage between shifting and continuous cultivation. Kudzu has the ability to establish itself on fairly impoverished soils and to quickly develop a lush green canopy underlain by plenty of nitrogen-fixing root nodules. After 1 or 2 years, the kudzu can be slashed with machetes and burned. Reasonable yields have been obtained by rotating two crops with 1 or 2 years of kudzu fallow (*26*). During the second rotation potassium is needed to obtain moderate crop yields. It appears that 1 to 2 years of kudzu fallow may have the same restorative effect on previously unfertilized, cultivated cropland as 25 years of forest fallow.

Technology is being developed for pasture production in sloping areas of Ultisols. The system would be based on the use of acid-tolerant grass and legume species selected by CIAT's Tropical Pastures Program. Promising germ plasm has been tested for adaptation in an Ultisol of *p*H 4.0 and 80 percent aluminum saturation with applications of only 50 kilograms of P_2O_5 as simple superphosphate and 50 kilograms of potassium per hectare. Results show that the grasses *Andropogon gayanus*, *Brachiaria humidicola*, and *B. decumbens* and the legumes *Desmodium ovalifolium* and *Pueraria phaseoloides* are well adapted to the soil, climate, and pest and disease constraints of the region (*37*). The grass and legume pastures are now being tested under grazing.

Many scientists believe that the natural vocation of the Amazon Basin is trees and that ultimately a tree canopy should replace crop or pasture canopies. Research is being initiated to combine crop production systems with promising tree species such as *Gmelina arborea*, oil palm, and pejibaye (*Guilielma gasipaes*). Figure 4 illustrates some of the alternatives. Agricultural land should be integrated with forest reserves in a mosaic pattern to avoid the potentially undesirable effects of large areas of cleared land.

Ecological Implications

Regardless of the many objections voiced against further clearing of the humid tropical forests, land-hungry farmers are migrating to these regions and to large urban centers already present in the Amazon Basin. Increasing demand for food at the national and world levels suggests that this trend will accelerate during the next decades. Our experience and data show that attempts to produce food crops or pastures in acid soils of the humid tropics on a sustained basis without correct technology are likely to fail. The key is correct technology, be it for annual crops or for legume-based, acid-tolerant pastures (*38*). With technology that is agronomically and economically sound, the situation can change from one that is ecologically damaging to one that will maximize production per unit area on a sustained basis. We believe that the continuous cropping technology can have a positive ecological impact where it is practiced appropriately, because for every hectare that is cleared and put into such production, many hectares of forest may be spared from the shifting cultivator's ax in his search to grow the same amount of food. People do not cut tropical rainforests because they like to, but because they need to grow food or fiber. Intensive cultivation of cleared land is one way to satisfy the food demands with minimum clearing. In fact, we hope that this technology will be interspersed with areas of virgin forests, pastures, and tree plantations in a way similar to the mosaic one now finds in much of southeastern United States, where shifting cultivation was the predominant system only a few decades ago.

Limitations

It would be unwise to assume that continuous cultivation technology is directly applicable to the millions of hectares of Ultisols and Oxisols in the humid tropics. Our work has concentrated on nearly level soils, thereby avoiding the erosion hazard of cultivating sloping lands. Landscape adaptations, including terracing such as is practiced in parts of humid tropical Asia, would be needed for continuous cultivation on sloping lands. Legume-based pasture or agroforestry appears more attractive for sloping lands. Our recommendation is to concentrate on the vast areas of nearly level land. In the Amazon there are 207 million hectares of well-drained Oxisols and Ultisols with slopes of 0 to 8 percent (Table 1).

Although weed, insect, and disease attacks were alleviated in this study by crop rotation, selection of varieties reasonably tolerant to pest attacks, and judicious use of insecticides and herbicides, pest control needs are likely to increase in the future. Experience in other regions with acid, infertile soils indicates that plant protection becomes a major problem once soil constraints are attenuated (*9*).

Another limitation is the variability in socioeconomic conditions. The Yurimaguas area, although hardly a privileged region of the Amazon Basin, has an unpaved road and a river which link it with the rest of the country—a rudimentary market system. Present socioeconomic conditions indicate a clear economic feasibility in Yurimaguas. It would be foolish to attempt continuous cultivation in areas with little market accessibility, unattractive cost: price ratios, or restrictive governmental policies.

Finally, the new technology must be tested locally to determine any necessary modifications. Such modifications might involve the use of different crop species, varieties, rotations, and certainly fertilizer rates. A simple but efficient soil fertility evaluation service, consisting of a soil testing laboratory and advisory services (*39*), is essential to assist farmers as they change to continuous cultivation.

References and Notes

1. *World Food and Nutrition Study* (National Academy of Sciences–National Research Council, Washington, D.C., 1977), vol. 4.
2. *Ecology and Development in the Humid Tropics* (National Academy Press, Washington, D.C., in press).
3. N. Myers, *Conversion of Tropical Moist Forests* (National Academy of Sciences–National Research Council, Washington, D.C., 1980).
4. P. T. Alvim, *Um Modelo Contra os "Mitos" da Amazônia* (Commissão Executiva do Plano da Lavoura Cacaueira, Itabuna, Bahia, Brazil, 1979).
5. *Agriculture Toward the Year 2000* (Food and Agriculture Organization, Rome, 1978).
6. A. Tanco, Jr., *Plenary Address to the Bonn Conference on Agricultural Production* (Rockefeller Foundation, New York, 1980).
7. *Priorities for Alleviating Soil-Related Constraints to Food Production in the Tropics* (International Rice Research Institute, Los Baños, Philippines, 1980).
8. C. E. Kellogg and A. C. Orvedal, *Adv. Agron.* 21, 109 (1969).
9. P. A. Sanchez and J. G. Salinas, *ibid.* 34, 279 (1981).
10. D. Marchetti and A. D. Machado, Eds., *Cerrado: Uso e Manejo* (Editerra, Brasilia, Brazil, 1980).
11. R. J. A. Goodland, *Environ. Conserv.* 7, 9 (1980).
12. H. Sioli, in *Land, People, and Planning in Contemporary Amazonia*, F. Barbira-Scazzochio, Ed. (Cambridge Univ. Press, Cambridge, 1980), pp. 257–268.
13. S. Brown, A. E. Lugo, B. Leigel, *The Role of Tropical Forests in the World Carbon Cycle* (Department of Energy, Washington, D.C., 1980).
14. ... Setzer, *Rev. Bras. Geogr.* 29, 102 (1967); R. J. A. Goodland and H. S. Irwin, *Amazon Jungle: Green Hell to Red Desert?* (Elsevier, Amsterdam, 1975); I. Friedman, *Science* 197, 7 (1977); G. Irion, *Naturwissenschaften* 65, 515 (1978).
15. C. F. Marbut and C. B. Manifold, *Geogr. Rev.* 16, 414 (1926).
16. Soil Survey Staff, *Soil Taxonomy* (Soil Conservation Service, Department of Agriculture, Washington, D.C., 197?).
17. *Soil Map of the World* (Unesco, Paris, 1971 to 1979), vols. 1 to 10.
18. T. T. Cochrane, J. A. Porras, L. Azevedo, P. G. Jones, L. F. Sanchez, *Explanatory Manual for CIAT's Computerized Land Resource Study of Tropical America* [Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia, 1979].
19. T. T. Cochrane and P. A. Sanchez, in *Amazon Land Use Research* (CIAT, Cali, Colombia, in press).
20. P. A. Sanchez and S. W. Buol, *Science* 188, 598 (1975).
21. H. Klinge, *J. Soil Sci.* 16, 95 (1965); *Amazoniana* 1, 303 (1968); *Acta Amazônica* 1, 69 (1971); *Trop. Ecol.* 16, 18 (1975); N. Stark, *Biotropica* 10, 1 (1978).
22. S. W. Buol, P. A. Sanchez, R. B. Cate, M. A. Granger, in *Soil Management in Tropical America*, E. Bornemisza and A. Alvarado, Eds. (North Carolina State University, Raleigh, 1975), pp. 126–141.
23. P. H. Nye and D. J. Greenland, *Commonw. Agric. Bur. Tech. Commun. 51* (1960).
24. P. T. Alvim, *Interciencia* 3, 243 (1978).
25. D. J. Greenland, *Science* 190, 841 (1975).
26. Detailed data are recorded in the Tropical Soils Program's annual reports (North Carolina State University, Raleigh, 1972, 1973, 1974, 1976, 1978, 1980, and 1982).
27. C. E. Seubert, P. A. Sanchez, C. Valverde, *Trop. Agric. (Trinidad)* 54, 307 (1977); P. A. Sanchez, in *Soils Research in Agroforestry*, H. O. Mongi and P. A. Huxley, Eds. (International Council for Research in Agroforestry, Nairobi, Kenya, 1979), pp. 79–124.
28. E. Gonzalez, E. J. Kamprath, G. C. Naderman, W. V. Soares, *Soil Sci. Soc. Am. J.* 43, 1155 (1979); K. D. Ritchey, M. G. Djalma, E. Lobato, O. Correa, *Agron. J.* 72, 40 (1980).
29. R. Mesía, D. E. Bandy, J. J. Nicholaides, *Agron. Abstr. 1979* (1979), p. 46.
30. D. G. Hernandez and A. J. Coutu, *Agron. Abstr. 1981* (1981), p. 47.
31. P. A. Sanchez and M. A. Nureña, *N.C. Agric. Exp. Stn. Techn. Bull. 210* (1972).
32. M. Piha and J. J. Nicholaides, *Agron. Abstr. 1981*, p. 45 (1981).
33. C. Valverde and D. E. Bandy, in *Amazon Agricultural Land Use* (CIAT, Cali, Colombia, in press).
34. R. Lal, *Int. Inst. Trop. Agric. Monogr. 1* (1975).
35. M. K. Wade, thesis, North Carolina State University, Raleigh (1978).
36. D. E. Bandy and J. J. Nicholaides, *Agron. Abstr. 1979* (1979).
37. M. Ara, P. A. Sanchez, D. E. Bandy, J. M. Toledo, *Agron. Abstr. 1981* (1981), p. 38.
38. J. M. Toledo and E. A. S. Serrão, in *Amazon Agricultural Land Use* (CIAT, Cali, Colombia, in press).
39. For examples of a successful system, see E. Bornemisza and A. Alvarado, Eds., *Soil Management in Tropical America* (North Carolina State University, Raleigh, 1975), pp. 455–532.

40. This is Paper 8240 of the journal series of the North Carolina Agricultural Research Service, Raleigh, in cooperation with the Instituto Nacional de Investigación y Promoción Agraria, Peru. Supported by contract AID/ta-C-1236 and the Soil Management Collaborative Research Support Program of the U.S. Agency for International Development. Work reported here reflects the contributions of J. Alegre, M. A. Ara, J. R. Benites, S. W. Buol, D. K. Cassel, R. B. Cate, A. J. Coutu, D. G. Hernandez, C. E. Lopez, R. Mesía, M. A. Nureña, M. Piha, C. E. Seubert, E. J. Tyler, C. Valverde, J. Van Diepen, and M. K. Wade.