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Amazon Basin: A System in Equilibrium

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The Amazon Basin has an area of about 5.8×10^6 km^2 and drains about one-third of the land surface of South America (*1*). The main channel of the Amazon River, that is, Urubamba-Ucayali-Amazon, is some 6500 km long from source to mouth (*2*) and has about 1000 tributaries. Oltmann's estimate (*3*) of the mean discharge, confirmed by more recent measurements (1982 to 1984) (*4*), of 175,000 m^3 sec^{-1} or a total discharge of 5.5×10^{12} m^3 year^{-1} is five times that of the Congo and represents 15 to 20 percent of the global freshwater supply.

Deforestation in the Amazon Basin has accelerated in recent years, especially in the Rondonia, Acre, and Mato Grosso regions of Brazil (*5*). The major changes in land use, and the associated population influx, must inevitably affect the ecosystem. The large scale of the Amazon should not obscure the fact that it is presently a system in equilibrium. We discuss it here from the point of view of a system that has achieved a steady state in its water cycle, nutrients, and energy balance. We also consider the possible consequences of man-induced disequilibrium.

Summary. Despite the very active deforestation of the last decade, the Amazon Basin is still primarily covered with trees and is a system in equilibrium. The Andes form a barrier at the western end of the basin and, coupled with the prevailing easterly winds, ensure an almost unique precipitation and water-recycling regime. On average 50 percent of the precipitation is recycled, and in some areas even more. The soils are poor. Most of the nitrogen and phosphorus is found in the soil, and the remaining nutrient elements are found in the standing biomass. There is some nutrient recycling and little loss from the intact ecosystem, and the small input of nutrients from precipitation maintains a small positive nutrient balance. Continued large-scale deforestation is likely to lead to increased erosion and water runoff with initial flooding in the lower Amazon, together with reduced evapotranspiration and ultimately reduced precipitation. Reduced precipitation in the Amazon could increase the tendency toward continentality and adversely affect climate and the present agriculture in south-central Brazil.

Water Cycle

The main influx of atmospheric water into the basin comes from the Northern Hemisphere trade winds. The Amazon climate is therefore characterized by mainly easterly winds. Rainfall ranges from 1500 to 3000 mm annually, averaging about 2000 mm in the central Amazon. In the eastern and western ends of the basin rains occur frequently throughout the year, whereas in the central part and in a portion of the western area of the basin there is a definite drier period. Here we must distinguish between the locally derived, relatively low cumulus clouds that seem to arise almost from the forest, and are initiated by latent and sensible heat (*6*), and the high-tropospheric clouds of the South American continent whose circulation, pattern, and influence on Amazon weather have recently been described by Kousky and Molion (*7*). The different rainfall regimes are determined by the interaction of the Intertropical Convergence Zone and the equatorial Atlantic air mass in the eastern region and by the presence of the equatorial continental air mass in the westernmost region. The rainfall regime of the central basin is determined by the expansion of the continental air mass in summer and by its contraction in winter.

Examination of aerial studies and Landsat imagery (*8*) has indicated no evidence of major north-south movements of water vapor within the basin, such as might be anticipated from the influx of air masses from the north. On the other hand, radiosonde studies (*9*) have indicated that some water vapor is exported south to Chaco Paraguaio and central Brazil, principally in March and December but to some extent in almost every month (*10*). Therefore, changes in the water regime of the Amazon Basin may have a direct effect on the rainfall of the Central Brazilian Plateau (*11*). It seems clear that the Andes form a natural barrier and prevent a major part of the water vapor from leaving the western end of the basin, as shown by the high levels (5000 mm) of precipitation in the Andean region.

In a situation where the horseshoe-shaped Amazon Basin experiences the main influx of water from the trade winds from the east and the apparent main efflux by way of the river to the east, major water-recycling effects might be anticipated through forest evapotranspiration. There is good agreement between evapotranspiration estimates obtained by more conventional climatological methods and those obtained by recent aerial and isotopic techniques.

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About 50 percent of the rainfall is evapotranspired as water vapor back into the atmosphere, of which about 48 percent falls again as rain (*8, 12, 13*). This mass of water returned to the atmosphere represents a very high recycling rate (*8, 14*), with a mean recycling time of about 5.5 days (*15*).

Such figures are averages over large areas, including nonforested areas, and are also influenced by water vapor exports. More detailed watershed studies of loss by interception by the forest, transpiration, and evaporation, based on actual measurements of water gain and loss, indicate much greater evapotranspiration for the high forest. In two studies (*16, 17*) carried out near Manaus, which has just over 2000 mm of rainfall per year, it was found that 18.7 and 25.6 percent of the rain was intercepted by the forest and evaporated to the atmosphere, 62.0 and 48.5 percent was transpired by the forest, while runoff accounted for 19.3 and 25.9 percent, respectively, for the two locations (Fig. 1). Combined evaporation and transpiration therefore represented as much as 80.7 and 74.1 percent at the two sites (*16, 17*). More intense rains resulted in greater throughfall.

Using measurements of the ^{18}O and D isotopes in rain and river waters, we found it possible to confirm (*8, 18*) the importance of reevaporated water for the water balance throughout the basin, and in particular to establish a model indicating the relation with the new oceanic water. Consider that the central east-to-west region of the Amazon Basin between 0° and 5°S is subdivided into eight 3° segments between Belém (48°30′W) and just west of Benjamin Constant (72°30′W). A model can be developed (Fig. 2), which suggests that in any one segment about half the rainfall is derived from evapotranspiration recycling within the segment area, whereas the other half comes from water vapor derived from the neighboring eastern segment conveyed by prevailing winds.

For the most westerly, Andean, end of the basin we do not have good knowledge of the influx or efflux of water vapor, or indeed of recycling. The influence of Pacific Ocean–derived water vapor seems minimal, as shown by negligible concentrations of marine Cl^- in upper Amazon precipitation and river waters (*19*). Satellite photographs suggest an anticlockwise circulation of clouds northward over the Colombian part of the basin.

Large-scale deforestation, if continued at current rates, must inevitably affect the present equilibrium of the water cycle, and we have considered these effects elsewhere (*20, 21*). It is now recognized (*22*) that clearing tropical forests reduces infiltration rates and generally increases runoff. Greatly reduced infiltration rates have been found to occur with clearance in Suriname (*23*) and in the Peruvian Amazon (*24*), especially when bulldozers are used to clear the land. Schubart reported (*25*) that on land derived from primary forest near Manaus infiltration rates of 5-year-old pasture were less than one-tenth of the rates for primary forest soil. Confirmation is obtained from other areas with a longer history of deforestation and conversion to agriculture. For example, in West Africa runoff from cultivated and bare soils was 20 or more times that from forest land (*26*). In Malaysia conversion of natural forest to rubber or oil palm doubled peak storm flows and halved low flows with greatly increased erosion. In one large catchment the low flows were reduced to one-quarter (*27*). The once major Motagua River in Guatemala is more than 50 percent reduced in volume, after the loss of 65 percent of the natural forests in the last 30 years (*28*).

An increase in peak flow associated with deforestation has been ascribed to the Peruvian upper Amazon by Gentry and López-Parodi (*29*), who found a statistically significant increase in the annual high water mark at Iquitos from 1962 to 1978. This conclusion has been disputed (*30*), primarily for reasons relating to the measurement base and the extreme variability. The problem of variability is a real one; for example, the historically high flood of 1953 occurred long before major deforestation was a factor. Nevertheless, the high annual floods experienced from 1970 onward and especially the high peak flows of 1981 and 1982, together with the commonly reported experience of riverside flooding, do suggest a direct connection with increased deforestation. Kempe noted (*31*) that the time of year of peak flow has shifted from May-June to June-July; he suggested that this is due to a higher mean annual discharge, which does not influence the peak flood level but causes the flood wave to shift.

Because the Penman equation (*32*) for estimating evapotranspiration can be applied to different vegetation types including, with slight modification, forest, it can lead to the belief that, when primary forest is replaced by some other type of vegetation such as pasture or annual crops, rainfall and the overall water balance of an area will not be changed. Hydrologists have been inclined to discount the possibility that changes in land

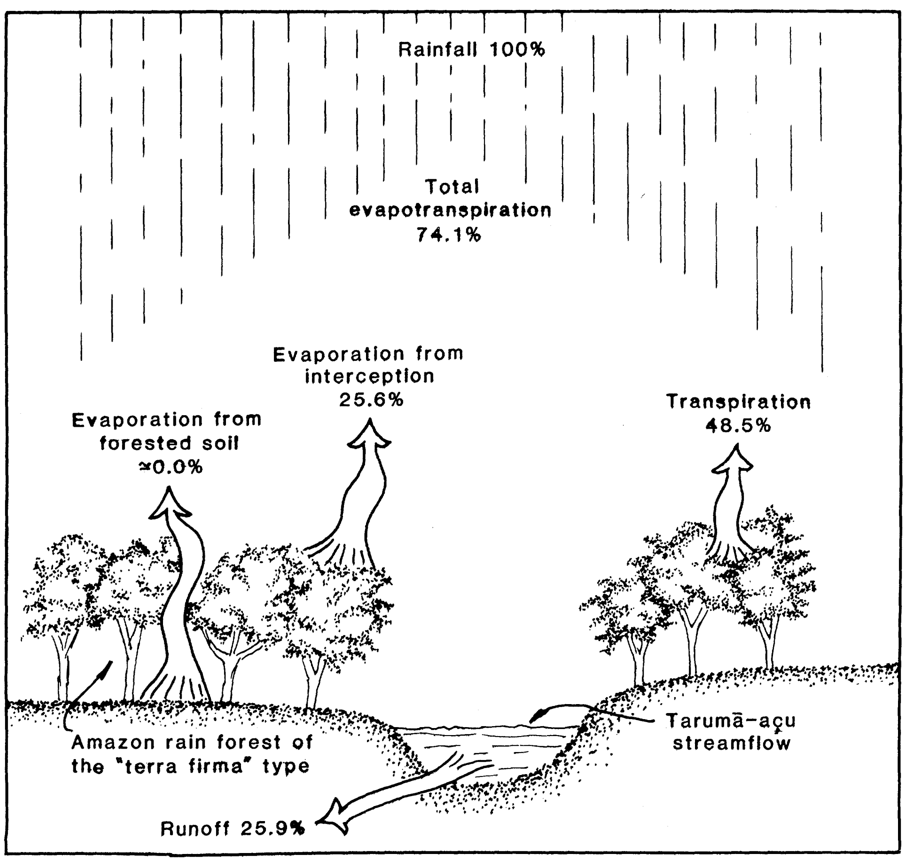

Fig. 1. Water balance from a study of a model basin near Manaus (*17*).

use can affect rainfall (33). This may be true if the area being converted is small in relation to the whole geographical-climatological zone and if the major proportion of the precipitation is advective and not dependent on recycling. However, it is almost certainly a fallacy where large amounts of water are being lost to the system through the greatly increased runoff associated with widespread deforestation and where the existing rainfall regime is greatly dependent on recycling.

Real loss of water from the Amazon water cycle is likely to be the major factor determining potentially adverse climatic change in this region. The forest canopy protects the forest floor from the direct impact of rain, and the surface debris and organic matter reduce runoff and ensure water absorption. The established vegetation increases percolation by maintaining a good soil structure, and both water recharge of the system and its release will take place relatively slowly. The disturbed soil will have reduced water absorption and shorter retention times than the forest soil it replaces. Salati and Ribeiro have reported (11) that deforestation will reduce the water residence time in the Amazon Basin, and they concluded that a 10 to 20 percent reduction in precipitation would be sufficient to cause considerable alterations to the ecosystem. The isotopic composition of rainwater varies with the season of the year, but time-comparable variation was not observed in drainage water (34). This result suggests a mixing of waters and high water storage in the soil of undisturbed forest.

The distribution of rainfall is also important, and, although there is adequate total annual rainfall throughout the basin, there is in many regions, for example, Manaus, a marked dry period. If a relatively small reduction in annual rainfall resulted in an extension of the dry period, this could have serious consequences. Fearnside (35) has noted that in Manaus in 1979 there was a period of 73 days without rain. If such long dry periods were to become commonplace or extended, there would inevitably be a marked change in the natural vegetation.

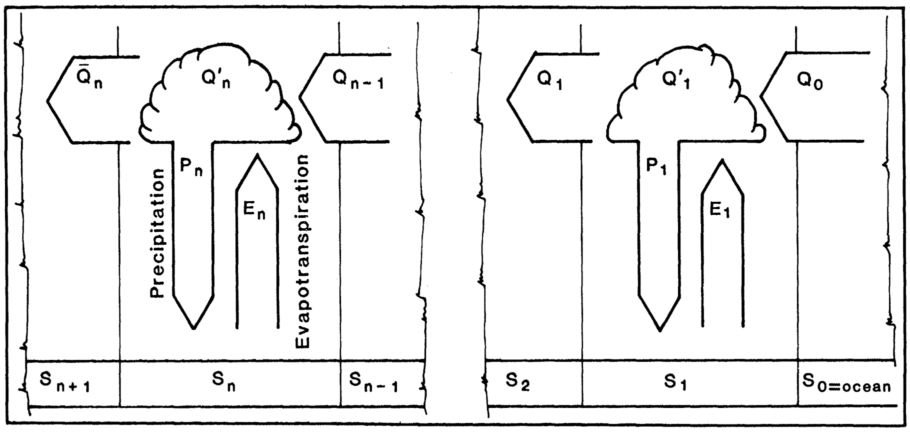

Fig. 2. Model to explain the distribution and recycling of rain (*P*) in the Amazon, assuming two sources of water vapor, the first from the ocean (*Q*) and the second from evapotranspiration (*E*). In any segment (*S*) about half the rainfall is derived from evapotranspiration recycling and half from water from the neighboring eastern segment (18).

Nutrient Balance, Gain and Loss

There is little quantitative information on nutrient recycling in the forests of the humid tropics, and the information that we have is fragmentary (36). The bulk of the stored nitrogen and phosphorus in the system is in the soil, roots, and litter of the forests, whereas the greater proportion of the cations, for example, Ca^{2+}, K^+, Na^+, Mg^{2+}, plus sulfur are in the standing biomass. In the mature forest system there is very little export or import of nutrients.

Klinge (37) carried out mineral analyses and constructed a balance sheet for soil and biomass of a high forest ecosystem near Manaus (Table 1). Only 20 percent of the total nitrogen and 27 percent of the total phosphorus are in the aerial parts, and by far the greatest proportion of both elements, of the order of 70 percent, is in the soil. In contrast, 66 to 80 percent of K^+, Na^+, Ca^{2+}, and Mg^{2+} are in the aerial parts. "Zero" Ca^{2+} was recorded in this soil of *p*H 3.5, as apparently long recycling has led to almost complete accumulation of this element in the biomass. Although there is no sign of nitrogen deficiency in the equilibrium forest, the large amount of nitrogen (12,201 kg ha^{-1}) is perhaps surprising. Of that, 2428 kg ha^{-1} was present in the aerial parts, representing a theoretical concentration of 0.59 percent nitrogen (dry weight). The amount of phosphorus in the aerial parts was very low (58.9 kg ha^{-1}), representing only 0.0145 percent.

Recycling in climax tropical forest is due to annual litterfall and the leaching of nutrients from leaves due to rain. There are some data (38–40) on litter

Table 1. Total amounts and distribution of major nutrient elements in a tropical high forest ecosystem (ferralsol, *p*H 3.5) near Manaus (37).

Component	Total in soil		Total in ecosystem	Portion of total in					
				Living biomass			Dead biomass (%)	Mineral soil	
				Aerial parts		Roots (%)		0 to 30 cm (%)	30 to 100 cm (%)
	0 to 30 cm	30 to 100 cm		%	kg ha^{-1}				
Nitrogen	4,263 kg ha^{-1}	4,661 kg ha^{-1}	12,201 kg ha^{-1}	19.9	2,427.8	4.6	2.4	34.9	38.2
Phosphorous	71 kg ha^{-1}	76 kg ha^{-1}	216 kg ha^{-1}	27.3	58.9	3.2	1.4	32.9	35.2
K^+	58 kg ha^{-1}	0 kg ha^{-1}	562 kg ha^{-1}	77.2	433.8	11.0	1.4	10.3	0.0
Na^+	35 kg ha^{-1}	15 kg ha^{-1}	291 kg ha^{-1}	66.3	192.9	15.5	1.0	12.0	5.2
Ca^{2+}	0 kg ha^{-1}	0 kg ha^{-1}	528 kg ha^{-1}	80.3	424.0	15.7	4.0	0.0	0.0
Mg^{2+}	17 kg ha^{-1}	6 kg ha^{-1}	298 kg ha^{-1}	67.8	202.0	18.5	6.0	5.7	2.0
Plant biomass			504 } 737 ton ha^{-1}	55.1		9.1	4.2		
Humus	113 ton ha^{-1}	120 ton ha^{-1}	233 }					15.3	16.3
Mineral soil (without humus)	3,349 ton ha^{-1}	9,373 ton ha^{-1}	12,722 ton ha^{-1}					26.3	73.7
Water	1,569 ton ha^{-1}	3,252 ton ha^{-1}	5,320 ton ha^{-1}	5.2		3.5	0.6	29.5	61.1

Table 2. Nutrient recycling in undisturbed South American primary forest.

Place	Litter (dry matter) (ton ha^{-1} year^{-1})	Nutrient recycling* via litter (kg ha^{-1} year^{-1})					Reference
		N	P	K^+	Ca^{2+}	Mg^{2+}	
Manaus, Brazil	7.3	106	2	13	18	13	(*38*)
Carare, Colombia	12.0	141	4	17	90	20	(*39*)
Mérida, Venezuela	4.6	57	3	20	31	12	(*40*)

*No data available for nutrient losses from tree foliage by rainfall leaching.

recycling (Table 2), and the amounts recycled annually are relatively small as compared with the total amounts likely to be in the standing biomass (Table 1). The amount of nitrogen recycled may be over 100 kg ha^{-1} year^{-1}, but the amount of phosphorus is as low as 2 to 4 kg ha^{-1} year^{-1}. Nutrient inputs to the undisturbed system come from the atmosphere as aerosols and precipitation and could be significant in areas being cleared by burning. Using proton-induced x-ray fluorescence analysis, Artaxo Netto *et al.* (*41, 42*) found that the total concentration of the natural Amazon aerosol was under 10 μg m^{-3}, one of the lowest natural backgrounds recorded anywhere. Carbon, nitrogen, and oxygen comprise the major portion of the substrate particles, and amount to 80 percent of the total mass of natural aerosols and 99 percent of aerosols from brushfire areas. Table 3 shows the results of typical analyses, and it is apparent that burning forest does add appreciably to the aerosol nutrient content. However, if one takes into account the area burned at any one time in relation to the total area, the amount of nutrients recycled by this means must be comparatively small. There seems to be agreement between the results of this and other work (*43*) that large-particulate matter of natural aerosols, such as aluminum, silicon, calcium, and iron, come from the soil, whereas fine particulates, such as sulfur and potassium, come from vegetation.

Input and output data for nitrogen have been calculated for a model basin (*44*) 60 km north of Manaus. For May and June 1980, the total mineral nitrogen inputs were 0.022 and 0.020 kg ha^{-1}, respectively, and the outputs were 0.017 and 0.009 kg ha^{-1}, respectively. Extrapolated to an annual basis, these figures are very low. Ninety percent of the nitrogen in the Amazon River is in organic form (*45*), and much greater total nitrogen values were calculated (*44*) from data for regional analyses of rain and river waters. These calculations indicated that 4 to 6 kg ha^{-1} year^{-1} are lost via the Amazon River and that a similar amount enters in rainfall. These values are similar to the early data of Sioli (*46*) for the input and output of nitrogen, phosphorus, and iron for the Rio Negro Basin. He found inputs and outputs not greatly different, with nitrogen and phosphorus inputs from rain slightly exceeding outputs and both very small in relation to the total.

There is very active biological nitrogen fixation in many Amazon ecosystems, and this has been estimated (*44*) to amount to a basinwide average of 20 kg of nitrogen fixed per hectare per year, although this seems rather a low figure. As input from precipitation and output to rivers are approximately the same, about 4 to 6 kg ha^{-1} year^{-1}, Salati *et al.* concluded (*44*) that losses of nitrogen by denitrification and volatilization would also be about 20 kg ha^{-1} year^{-1}. The overall nitrogen balance for the whole basin was estimated to amount to an input of 36×10^8 kg year^{-1} from precipitation plus an input of 120×10^8 kg year^{-1} from biological nitrogen fixation and a loss of 120×10^8 kg year^{-1} from denitrification and volatilization. Jordan *et al.* (*47*) found in the Venezuelan Amazon a total of 5583 kg of nitrogen per hectare in the biomass plus soil (60 percent in soil); the major inputs were from $NH_4^+$$-$N in precipitation (11.3 kg ha^{-1} year^{-1}) and from nitrogen fixation (16.2 kg ha^{-1} year^{-1}), with $NO_3^-$$-$N (5.7 kg ha^{-1} year^{-1}) lost by leaching plus nitrogen (2.9 kg ha^{-1} year^{-1}) lost through denitrification. There is a positive nitrogen balance of 18.9 kg ha^{-1} year^{-1}.

"Average" Amazon rainwater (*19*) has the following composition (in micromoles per liter): Na^+, 12.4; K^+, 1.0; Mg^{2+}, 1.2; Ca^{2+}, 1.1; Cl^-, 13.7; SO_4^{2-}, 5.1; NO_3^-, 2.1; NH_4^+, 0.5; and silicon, 0.0. Assuming an annual rainfall of 2000 mm, one can calculate that the average inputs of nutrient ions (in kilograms per hectare per year) are as follows: Na^+, 5.7; K^+, 0.78; Mg^{2+}, 0.58; Ca^{2+}, 0.88; Cl^-, 9.7; and SO_4^{2-}, 9.8. Such inputs are not large, but, as Venezuelan workers have shown (*47*) the forest has a whole series of mechanisms for the entrapment and conservation of nitrogen and nutrient ions from precipitation. These include mycorrhizae, rapid turnover of small roots, epiphylls which adsorb cations, sclerophyllous leaves and thick bark which prevent leaching, and slow release of nutrients from the surface layer of organic matter.

Thus, the effect of deforestation is likely to alter the nutrient balance through loss rather than through recycling. This loss will initially consist of the nutrients in the standing biomass (Table 1), but later there will be leaching losses from the disturbed soil. Forest is normally cleared by burning, which results in major loss of sulfur and nitrogen. Nevertheless, the total amounts of nitrogen added through the ash (1.4 to 1.7 percent) are high, as high as 127 kg ha^{-1} for

Table 3. Concentrations (in nanograms per cubic meter of air) of elements in Amazon aerosols (*42*).

Element	Concentrations in natural forest aerosol 60 km north of Manaus	Concentrations in typical aerosols from forest burning area, valley of Rio Madeira		
Al	43.59	6,264	0	3,678
Si	74.41	31,812	11,900	43,819
P	13.30	20,172	24,667	6,476
S	374.10	18,254	21,890	11,268
Cl	72.99	9,170	11,906	8,799
K	189.90	42,378	54,444	15,969
Ca	24.81	37,345	13,193	4,293
Ti	7.04	1,234	347	2,053
V	9.36	2,066	209	48
Cr	3.72	143	0	492
Mn	0.82	2,405	1,074	101
Fe	37.96	2,816	633	2,725
Ni	1.95	0	290	0
Cu	0.23	434	115	20
Zn	9.31	318	489	94
Br	1.66	727	0	147
Pb	5.01	1,482	237	48

a 25-year secondary forest burned at Yurimaguas, Peru (*48*), and 96 kg ha^{-1} for tropical forest similar to the Amazon at Turrialba, Costa Rica (*49*). Only 20 to 25 percent of the total nitrogen is lost through burning, whereas most of the K^+, Ca^{2+}, and Mg^{2+} is retained in the ashes (*48–50*). Nitrogen can be rapidly lost from the ashes with rain, as much as 15 percent with the first rainfall (*51*). Cations are similarly affected by rain and are leached from the surface soil (20 cm) (*52*). Salas and Folster (*50*) found that for a rather thin forest in Colombia losses on felling and burning were 30 to 80 kg of Mg^{2+} per hectare, 100 to 240 kg of Ca^{2+} per hectare, 60 to 140 kg of K^+ per hectare, and as much as 1300 to 1400 kg of nitrogen per hectare, including soil losses. Calculations suggested that rainfall inputs would make good the losses of cations in 10 to 20 years, on the assumption that forest regeneration were to occur, but that nitrogen fixation might restore the lost nitrogen in less time.

Traditionally much of the tropical forest areas have been farmed by shifting cultivation, under which land is cleared by burning and then a crop is grown for 2 or 3 years until yields decline and the cultivator moves on. With most of the nutrients accumulated over many years present in the ash, it is not surprising that the first crop after burning and clearing is good. The second crop, without the addition of fertilizer, is much poorer, and the third crop is either very poor or a total failure. The decline of fertility of cleared Amazon forest soil under poor management is typified by the degraded pasture area of Paragominas, situated in Pará State south of Belém. This area was extensively cleared for pasture, primarily *Panicum maximum*, and typically did not receive any fertilizer or legumes. There are now approximately 500,000 ha that are substantially degraded (*53*), and severe erosion is extensive, with part of this erosion due to overgrazing.

Typical Amazon forest soils have low *p*H, very high concentrations of exchangeable Al^{3+} and organic matter, and low concentrations of exchangeable cations and available phosphorus (Tables 4 and 5). When forest is cleared by burning, a large proportion of the nutrients are retained with the ash. At Paragominas, the effects are visible (Table 5) in the pasture a year afterward: *p*H is increased, exchangeable cations and phosphorus are increased, exchangeable Al^{3+} and aluminum saturation are greatly reduced, and there is a relatively small decline in organic matter. At the end of 7 years when degradation has occurred, there has been a reduction in (Ca^{2+} + Mg^{2+}) and a drastic decline in available phosphorus, a slight decline in nitrogen, *p*H remains 5.7 to 6.0, while organic matter has stabilized. It seems a general rule (*54*) that the organic matter of tropical forest soils declines about 25 percent on conversion from forest to cultivation, mostly in the first year, and thereafter the level appears to stabilize, rather contrary to accepted opinion. Although the general nutrient levels at Paragominas are not high, clearly lack of phosphorus has been the major limiting factor, and it has been shown (*53*) that addition of phosphorus greatly assists regeneration.

This analytical case history of a pasture soil is probably typical also of shifting cultivation sites in the Amazon, but results from Yurimaguas show that with modest use of fertilizer the case history can be different (*55*). Here, after 20 crops of upland rice, maize, and soybeans over a period of 8 years and with regular application of fertilizer, the soil showed the following composition: 1.55 percent organic matter, 4.98 meq of Ca^{2+}, 0.35

Table 4. Composition of soils of typical central Amazon high forest: Rio Madeira (*49*) and near Manaus (*82*). Data were averaged for a depth of 0 to 20 cm.

Location	Organic matter (%)	*p*H		Exchangeable cations (meq per 100 g)					Cation-exchange capacity
		H_2O	KCl	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	
Rio Madeira (*49*)									
100 km south of Porto Velho "Latossolo vermelho-amarelo" (red-yellow latosol)	3.16	4.7	3.6	0.17	0.10	0.10	0.02	1.3	2.80
Near Humaita "Laterita hidromorfica" (ground-water laterite)	3.00	4.3	3.8	0.04	0.06	0.10	0.01	2.5	4.32
100 km north of Humaita "Podzolico vermelho-amarelo plintico" (plinthic red-yellow podzol)	4.80	3.7	3.4	0.04	0.15	0.19	0.02	5.0	4.74
Experimental basin 60 km north of Manaus (*82*) "Latossolo amarelo, álicos argilosos" (clayey allic red-yellow latosol)	4.1	4.3	3.7	0.24	0.06	0.03	0.02		8.75

Table 5. Changes with time in the composition of an Amazon forest soil converted to *Panicum maximum* pasture; region of Paragominas, Pará State (*83*).

Sample	Organic matter (%)	Nitrogen (%)	*p*H (H_2O)	Ca^{2+} + Mg^{2+} (meq per 100 g)	Al^{3+} (meq per 100 g)	K^+ (ppm)	Phosphorus (ppm)	Aluminum saturation (%)
Forest soil before clearance by burning	2.79	0.16	4.4	1.47	1.8	23	1	53
After 1 year of pasture	2.04	0.09	6.5	7.53	0.0	31	10	0
After 3 years of pasture	3.09	0.18	6.9	7.80	0.0	78	11	0
After 4 years of pasture	2.20	0.11	5.4	3.02	0.2	62	2	6
After 5 years of pasture	1.90	0.10	5.7	2.81	0.2	66	3	6
After 6 years of pasture	1.90	0.09	6.0	3.84	0.0	74	7	0
After 7 years of pasture	1.77	0.08	5.7	2.61	0.0	47	1	0

meq of Mg^{2+}, and 0.11 meq of K^+ (all per 100 g of soil), with an aluminum saturation of only 1 percent and 39 ppm of available phosphorus. Moreover, a more favorable environment for deeper root development has been gradually created. Although the technology used at Yurimaguas is probably not, as we discuss later, the answer for the whole of the Amazon, it does show that soil degradation and loss of nutrient ions are not an inevitable part of forest clearance and cropping.

Probably of more importance than loss of nutrients is soil erosion, which has been, to a greater or lesser extent, the almost inevitable consequence of deforestation and conversion to cropping in other tropical areas (*26, 56*). There are those who believe that erosion from the central Amazon Basin is not likely to be serious because the terrain is generally flat (there is a drop of only 60 m for the 3000-km Brazilian section of the main river, or a slope of 2 cm km^{-1}). In fact, the topography of the basin shows a series of small hills, some with quite steep slopes. A false impression of the terrain can be obtained from the use of large-scale topographic maps (*35*).

Total sediment and nutrient losses at the mouth of the Amazon are the summation of losses from three distinct types of rivers. The "blackwater" rivers originate from the white, sandy, poor, acid soils of the central Amazon, which characteristically have a surface mat of partly decomposed organic matter. The Rio Negro is typical of such rivers, which are extremely poor in nutrients but carry much suspended humic matter, from which they derive the color and name. The "whitewater" rivers, of which the Rio Solimões and the main channel are characteristic, carry high sediment loads derived from Andean erosion. The "clearwater" rivers are similar rivers from old eroded areas at the north and south edges of the basin. The little sediment that they originally contain completely settles out in "lakes" near the junction with the receiving river. An important feature of Amazonia is the *varzea*, that is, alluvial land that is subject to annual flooding at peak river flows and is capable of supporting the most productive agriculture in the basin. During flooding the new silt brought in by the river must more than make up for nutrient losses caused by leaching, but undoubtedly the nutrient relations are complex, and we have little information. It has been calculated (*57*) that the *varzea* floodplain covers an area as large as 100,000 km^2 along the main channel, which becomes a lake at peak discharge. Parts of the *varzea* are flooded for as long as 6 months at a time.

The analyses of various investigators (*3, 19, 45, 58–61*) have provided substantial information concerning the total water discharge and the solid and dissolved materials, including carbon and important nutrient ions, transported by the Amazon. Gibbs's data (*59, 60*) provide a useful basis for discussing both erosion and water chemistry, partly because the results are based on wet- and dry-season sampling, and particularly because the data were obtained well before the recent and current large-scale deforestation.

The rates of erosion and the amounts of solid and dissolved matter transported are shown in Table 6. Gibbs concluded (*59*) that the greatest influence on erosion and the total matter transported was relief. Thus 84 percent of the total load comes from the Andes, which amounts to only 12 percent of the catchment area. The total annual erosion was calculated as 116 ton km^{-2} $year^{-1}$, equivalent theoretically to a little less than 0.05 mm $year^{-1}$. Clearly, as the data are skewed by the Andean contribution, overall erosion in the central basin was quite low at that time. The proportion of dissolved matter was about one-third of the total load for the whitewater rivers, increasing to 50 to 85 percent for the blackwater rivers. The total of solid and dissolved matter (734×10^6 ton $year^{-1}$) is smaller than the total sediment flux (900×10^6 ton $year^{-1}$) later measured at Obidos by Meade *et al.* (*61*). This may represent a genuine increase between sampling years but possibly reflects different sampling procedures. The latter data are not based on seasonal cycle sampling, and Sioli (*58*) noted that there was a fourfold variation in the suspended load between dry and rainy seasons.

Table 6. Average erosion rate and transport of solid and dissolved matter in the Amazon system (*59*).

River basin	Erosion rate (ton km^{-2} $year^{-1}$)	Solid plus dissolved matter (10^6 tons per catchment area)	Dissolved matter (% of total)
Mountainous			
Ucayali	459.1	186.1	33
Marañon	344.4	140.1	27
Intermediate			
Napo	213.1	26.0	14
Içá	78.8	11.7	22
Japurá	131.1	66.3	48
Madeira	199.7	215.4	27
Tropical			
Javari	79.8	8.5	14
Jutai	45.8	3.4	11
Juruá	82.6	17.9	40
Tefé*	14.6	0.4	85
Coari*	15.2	0.8	87
Negro*	20.0	15.1	50
Purús	73.5	27.3	41
Tapajós†	5.0	2.5	76
Xingú†	4.0	2.0	75
Araguari	17.2	0.8	56
Amazon (mouth)	116.0	730.3	32

*Blackwater rivers. †Clearwater rivers that have also sedimented out before the point of sampling.

Table 7 shows that the minimum and maximum concentrations of Ca^{2+}, Na^+, K^+, SO_4^{2-}, NO_3^-, and HCO_3^- vary by a factor of 2 to 3, as confirmed later by other workers. Maximum and minimum concentrations of PO_4^{3-} and Fe^{2+} show even greater spread. In contrast, SiO_2, Cl^-, and Mg^{2+} showed relatively little change in concentration through the year. It appears that minimum salinity occurs about 2 months after maximum discharge (*3*); a period of time thus seems to elapse before the system attains a new salinity equilibrium after seasonal discharge.

It can be postulated that the elements that show varying concentrations are the result of a constant supply diluted by a varying amount of water at different times of the year. Such a situation might arise where ions derive from source rock and where a major rapid increase in precipitation is not matched by the solubilization of ions. Stallard's calculations (*62*) support this idea in part and suggest that 40 to 60 percent of Ca^{2+}, Mg^{2+}, Na^+, and sulfur and as much as 90 percent of Cl^- are derived from Andean headwater sources, but that most of the K^+ and silicon transported by the river comes from weathered basin soils. Gibbs suggested (*60*) that both Cl^- and Na^+ were derived primarily from precipitation, on the basis that the Cl^-/Na^+ ratio of river waters approximates at maximum discharge the value for seawater, and that Cl^- has apparently few sources other than precipitation. Recent work does not support precipitation as a major source, and Stallard and Edmond (*19*) have calculated that the proportion of "cyclic salts," that is, atmosphere-derived salts ultimately returned to the oceans, makes only a minor contribution to the chemistry of the Amazon. They estimated that the proportion of cyclic salts in the dissolved load at Obidos (about 80 percent of Amazon waters) was as little as 17.6 percent Cl^-, 0.9 percent Na^+, 1.3 percent Mg^{2+}, 3.6 percent sulfur, 0.4 percent K^+, and 0.1 percent Ca^{2+}.

Kempe recently reviewed (*31*) a number of cycles of river analyses and found that the concentration of dissolved solids peaks in March when Andean-derived water reaches Obidos; when waters rise farther, the concentrations decline substantially, increasing slightly again as the water level drops. Concentrations vary by a factor of 2.5 over the year, thus confirming the postulation of Gibbs (*60*). The maximum SiO_2 concentration uniquely occurs well after the total dissolved solids have reached peak concentration and after the main rise in water. This finding tends to support Stallard's (*62*) suggestion that silicon comes from the lowland area, as these waters reach Obidos after the upland river waters. On the Rio Negro, phosphorus, total PO_4^{3-}, total iron, and dissolved iron tend to peak as the waters recede; this finding suggests that these components are a result of leaching, but the total amounts are small (*46*).

We should stress that brief interpretations such as those discussed in this section are gross oversimplifications, as we are dealing with very complex systems. As Richey has recently reported (*57*), the river, its sediments, and the *varzea* may store carbon, nitrogen, phosphorus, sulfur, and probably other elements for substantial periods of time. What does seem clear, however, is that at present the major output of nutrients at the mouth of the Amazon is primarily due to Andean erosion. There appears to be comparatively little loss from the stabilized soils of the central basin itself.

Table 7. Composition and mass transport rate of the dissolved salts of the Amazon River (*60*).

Component	Dissolved salt concentration (mg liter^{-1})			Mass transport rate (10^6 ton year^{-1})
	Minimum	Maximum	Average	
HCO_3^-	15.0	33.5	22.5	124
SO_4^{2-}	1.7	4.7	3.0	17
Cl^-	3.2	5.0	3.9	22
NO_3^-	0.1	0.3	0.2	1.1
PO_4^{3-}	0.01	0.25	0.04	0.22
Ca^{2+}	3.9	10.4	6.5	36
Na^+	1.94	5.25	3.1	17
Mg^{2+}	0.81	1.40	1.0	5.5
K^+	0.4	1.35	1.0	5.5
SiO_2	9.1	12.42	11.2	62
Fe^{2+}	0.002	0.1	0.03	0.16
Al^{3+}	0.02	0.06	0.04	0.22
Total	39.4	73.1	52.9	292

Heat Balance and Climatic Change

Sunlight intensity in the central Amazon is high, reaching at the limit of the earth's atmosphere a maximum of 885 cal cm^{-2} day^{-1} in January and falling to a minimum of 767 cal cm^{-2} day^{-1} in June. The incident energy reaching the ground is much less but has a relatively high value, 559 cal cm^{-2} day^{-1}, in April (*63, 64*). The mean daily radiation at Manaus for the period 1977 to 1979 was 373 cal cm^{-2} day^{-1} (*64*). There is a high frequency of cloudiness, and the number of hours of sunlight is only about 50 percent of the theoretical maximum.

Mean monthly temperature shows little variation. At Belém, the mean maximum temperature of 26.9°C occurs in November and the mean minimum temperature of 24.5°C occurs in March. The corresponding mean montly maxima and minima for Manaus are 27.9°C (September) and 25.8°C (April), and for Iquitos are 32°C (November) and 30°C (July). North and south of the basin, toward the high plateau of Guyana and the plateau of central Brazil, there is greater continentality, with well-defined dry periods and lower temperatures. In the Andean region, low temperatures are common and at the higher levels the most significant precipitation is in the form of snow. Important phenomena that can cause major variations in temperature, sometimes with ecological consequences, are the "friagem" or cold spells that occur when air masses originating in the South Polar region hit the central and western parts of the basin, when temperatures can fall to about 14°C.

Removal of forest and substitution by other vegetation must inevitably affect the atmospheric heat balance, because with this change the albedo (the ratio of reflected to solar energy) increases. Forests have the lowest albedo, deserts the highest, with savannah intermediate; forest removal increases the albedo from about 0.13 to 0.16 (*65*). Therefore, the amount of solar energy absorbed by the ground cover is reduced and more energy is reflected and lost to space, whereas the energy available for heating the overlying air and for convection is also reduced. Albedo values have not been determined specifically for the Amazon Basin, and those used by different workers have varied somewhat (*66*).

The energy and hydrological cycles are closed linked. The energy absorbed by both the forest and the bare ground is returned to the atmosphere as sensible and latent heat. Sensible heat is the result of the cooling of ground cover by the passage of air, and the heat transferred from the surface warms the earth's atmosphere directly. Latent heat is derived from the energy lost by leaf, soil, and other surfaces when water is vaporized through evapotranspiration. This heat is then subsequently released as sensible heat during the formation of clouds. The ratio of sensible heat (*H*) to latent heat (*E*) (the Bowen ratio, $B = H/E$) can be substantially modified by forest removal, although such heat-flux changes are changes not in the net energy absorbed but rather in the exchange of energy between the surface and the atmosphere. What weight should be given to albedo effects as compared with the change to be expected in the Bowen ratio? Fränzle claimed (*13*) that quite a large change in albedo does not yield an essential change in the production of sensible and latent heat. However, the Bowen ratio can be substantially altered by deforestation, and, as sensible heat remains essentially the same in the short term, we are primarily examining potential changes in evapotranspiration (*E*).

Molion and Bentancurt (*67*) have demonstrated that evaporation differences among cover types, assuming water is not limiting, can be quantitatively explained purely in terms of energy considerations, and that forests evaporate more water than any other type of cover, as much as twice that from bare soil. There are also good practical reasons why this is so: water recharge of the forest soil is good and the tree roots exploit a large volume of soil, as they can tap water at greater depths than most annual crops or replacement vegetation. Nevertheless, evaporation from bare or partially covered soil can be high, even though theoretically the increase in albedo from deforestation should result in decreased absorption of solar energy. On a local scale, without the shade of the forest canopy, greatly increased solar radiation reaches the soil surface. In virgin forest in Guatemala only 4 percent of the solar radiation reached the soil surface, and the solar energy reaching cleared soil was 25 times as much (*68*). In Ghana forest clearance led to an increase in the maximum soil temperatures at a depth of 7.5 cm from 27° to 38°C (*69*). Although the rate of evaporation from bare soil after rain may be very rapid, as is self-evident to anyone familiar with the tropics, this is a short-term phenomenon that affects only the surface soil; without further rain vapor the flux will rapidly decline as the top soil dries out, whereas the forest will continue evapotranspiring water from deeper soil. Although the grass cover may show a high rate of evapotranspiration the runoff is also high.

There is no knowledge of "scaling effects" on evapotranspiration in the Amazon, or anywhere else (*21*). Within the small clearings of shifting cultivation there is likely to be little detectable effect as the moist air from the surrounding forest will swamp any drier air. Since the recycling of water in the Amazon Basin will have been reduced by a small amount, the cumulative effect of a large number of clearings could be large. Because the rate of evapotranspiration is determined by the saturation deficit and temperatures, the additive effect of dry air from large cleared areas on the remaining forest could be considerable. It has been observed that after long periods of drought the outer trees of the forest next to cleared land are the first to show signs of stress. One, possibly extreme, suggestion (*13*) is that extensive destruction of the forest could lead to a Bowen ratio exceeding 2.0. This suggestion implies that previous source areas of latent heat would become foci for the generation of large amounts of sensible heat.

Salati *et al.* (*21*) have postulated that widespread deforestation of areas such as the Amazon, where the rainfall regime is especially associated with recycling, sets in motion a chain of events. There is an immediate increased surface runoff, such water is rapidly lost to the rivers and ocean, without the possibility of its recharging the soil system and of its recycling through transpiration and precipitation. Evapotranspiration will continue at a high although reduced rate, returning moisture to the atmosphere, but it is drawing from a decreasing soil water store. Therefore, ultimately there will be a reduction in the amount of water recycled to the atmosphere and hence diminished local cloud cover, and diminished precipitation, with the net effects that there will be less total water in the system and an increase in solar radiation. The close connection between forest and low cumulus has been shown by satellite photographs (*70*). Amazonian rivers stand out as cloud-free areas, and part of this contrast is due to the reduced latent and sensible heat distribution over the rivers as compared with that over land. Even on commercial airline flights, it is possible to see that the cumulus cloud sometimes arises from the very top of the forest and that, where the forest thins out as a result of development, there is less cloud.

A number of attempts have been made to model the potential climatic effects of Amazon deforestation. Potter *et al.* (*71, 72*) used a two-dimensional zonal atmospheric model, assuming a rather extreme albedo change from 0.07 to 0.25 (*71*) and assuming an increased runoff rate and decreased evaporation rates. Their results anticipated a decrease in precipitation of 230 mm $year^{-1}$ between 5°N and 5°S. Lettau *et al.* (*14*) used essentially a surface energy balance model which took into account profiles of precipitable water in the atmosphere, exchangeable soil moisture, and annual mean profiles of surface and air temperature. They assumed that evapotranspiration would increase as a consequence of deforestation, and the model required a Bowen ratio that was dependent on the sum of sensible and latent heat fluxes remaining constant as evaporation changed; that is, changes in absorbed solar radiation had to be balanced by the net emission of thermal infrared radiation. The results suggested a warming of less than 1.5°C and, somewhat surprisingly, an increase in precipitation of 75 mm $year^{-1}$. Henderson-Sellers (*73*) used the three-dimensional general circulation model of the Goddard Institute for Space Studies, which included seasonal albedo changes and the moisture-holding capacity of soil. Her results suggested a decrease in rainfall of 600 mm $year^{-1}$ and a small temperature increase.

These results are clearly contradictory, and this in part derives from differences in the nature of the models and in the essential assumptions. The global procedure of Potter *et al.* (*71, 72*) has an advantage in that it does not have artificial boundaries, but it has the disadvantage of relatively poor resolution. The models of Lettau *et al.* (*14*) and Henderson-Sellers (*73*) were clearly Amazon-focused, but they differ in that the latter is atmospheric-based whereas the former depends on surface energy balance. The prediction (*14*) of a precipitation increase as a result of deforestation appears scarcely credible and seems to arise from the overreliance of the model on evapotranspiration and in particular on the assumption that evapotranspiration increases with deforestation.

Although primarily concerned with albedo change in semiarid regions of Africa, the model of Charney *et al.* (*74*) supports our general thesis. Charney *et al.* suggested regional reduced precipitation and perhaps high temperatures, resulting from an increase in albedo together with a major decrease in evapotranspiration. The original model of Potter *et al.* probably overestimates the albedo effect, but their assumption of increased runoff rate and decreased evaporation rate seems realistic, and the results are in the correct direction. We are not experts in climatic modeling, but from the considerations outlined above in particular, recycling of precipitation, the real loss of water from the soil system, and the scale effect of clearing unprecedentedly large areas of forest, we believe that the Henderson-Sellers (*73*) estimate of a decrease in Amazon rainfall of about 600 mm $year^{-1}$ is, to date, the most reasonable interpretation of the situation.

Potential Consequences of Disequilibrium

The latest official figures (*75*) for Brazilian Amazon deforestation suggest that at the present time at least 2.3 million hectares of forest are being destroyed each year, and for reasons discussed elsewhere (*5, 20*) the area might well be greater. Changes are inevitable, but to what extent we still cannot predict. The tropical forests of Amazon, Africa, and Southeast Asia (especially Indonesia and Malaysia) have hitherto occupied 50 percent of the land area of the 20° equatorial belt and make the largest contribution to global latent heat flux. This flux is transferred, in the form of clouds, by the atmospheric general circulation to balance the negative radiation flux of the polar regions. For this reason Newell (*76*) suggested that removal of tropical forests in the Amazon and Indonesia might have major effects on the general atmospheric circulation and therefore have consequences far beyond the tropics. So far this idea remains just a possibility, as there is no really good indication from modeling studies that major direct intercontinental effects will result from Amazon deforestation. Potter *et al.* (*71*) suggested that there might be a small decrease in precipitation of 1.5 to 2.0 percent in latitudes above 45°N, whereas Henderson-Sellers (*73*) thought the only global perturbation would be the result of a small addition of carbon dioxide. Recently Dickinson (*66*) concluded that global climate changes due to even complete tropical deforestation are not likely to be larger than natural climate fluctuations but that regional climate changes are likely to be considerably larger.

Although the trend of opinion is reassuring it should be emphasized that we do not really know very much about this question. The number of modeling studies is quite small and they all have limitations (*77*). Much more study is needed before it will be possible to be reasonably sure of the consequences of tropical deforestation on global climate. At present, we feel fairly certain that Amazon deforestation will cause major changes in the basin itself, especially if the prediction (*73*) of an average decrease in precipitation of 600 mm $year^{-1}$ is correct. In the region of Manaus the present dry period is already the maximum that the ecosystem can withstand, and any lengthening of the dry period, or possibly reduced rain at other periods, would induce irreversible changes. At present, forest fires do not start naturally in the Amazon because of the humidity. A reduction in rainfall can be expected to change this situation: it would not be possible to control such fires by human intervention. Rather perversely, despite predicted long-term reduced precipitation, there are already signs that we can expect deforestation in the upper Amazon to lead to an increased frequency and degree of flooding of the *varzea* in the lower Amazon. This will affect the agricultural production of some of the basin's most fertile soils.

The effects of reduced precipitation in the basin would probably be felt in Brazil beyond the immediate area. The climate of South America is determined primarily by the general circulation of the atmosphere and the oceans. Nevertheless, there is a certain amount of continentality with local control factors in the Amazon. A reduction in the precipitable water in the basin could mean that there would be less water available for export to the Chaco Paraguayo and central Brazil. A drier regime in the Amazon Basin and reduced rainfall in central Brazil could strengthen the tendency to continentality, which might affect climatic patterns and agriculture in south-central Brazil.

For example, the *cerrado* region of the altiplano already suffers from too little precipitation, and the current type of agriculture of São Paulo State is precariously balanced in terms of frost. During the winter of 1981 in the interior of São Paulo, near Piracicaba, all bananas were killed off by frost, sugarcane leaf tips were frost-burned, and a substantial part of the orange crop of the Limeira region was lost. Any shift toward continentality that either extended the winter period or induced lower winter temperatures could completely change the agriculture of the region. This would mean the loss of the valuable export production of sugar, oranges, and coffee, grown on some of Brazil's best soils, and a major setback to the import-saving alcohol fuel program.

Deforestation of the Amazon is likely to affect major natural systems beyond our present comprehension. Therefore, it is highly advisable that very large areas of forest should be retained and that policies for development should be directed toward sustained utilization. Annual cropping systems are appropriate for the relatively good soils of Rondonia, Acre, and the Peruvian Amazon, but for most of the Brazilian Amazon rational development should aim to preserve as much of the forest canopy as possible. This means the development of managed forestry. *Pinus caribaea* grows well there as does the valuable jacaranda [*Dalbergia nigra* (*78*)], together with tree crops such as cocoa, palm, rubber, and coffee under shade. Agroforestry systems, with the integration of small-scale production of cassava, dryland rice, maize, and grain legumes, together with managed forestry, offer the possibility of supporting food needs while maintaining the water cycle and restricting erosion. Large-scale clearance for cattle pasture and annual crops grown in large exposed fields would, according to our present knowledge, be the worst type of Amazon development, leading to major water runoff, erosion, and soil degradation, and the greatest possibility of induced climatic change.

Disequilibrium will have major impact on Amazon animals, indigenous peoples, and the flora (*79*). There remains a wealth of still unresearched exotic plant and animal life in Amazon that is in danger of being lost, even with the extensive reservations that are being established (*80*). There are over 23,000 identified plant species but countless others waiting to be discovered (*81*). Most of the existing plant species have not been screened to determine whether they have properties that might be valuable for medicine or industry, and rapid major changes may cause their loss with no chance of recovery.

Much data on the Amazon natural system are lacking, and many data are unreliable. Base-line studies are urgently needed, so that potential changes can be better understood.

References and Notes

1. L. de C. Soares, in *Geografia do Brasil, Região Norte* (Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, 1977), vol. 1, p. 95.
2. J. C. Magalhães Filho, *Rev. Bras. Geogr.* **22** (No. 1), 99 (1960).
3. R. E. Oltmann, *Atlas do Simpósio sobre a Biota Amazônica*, vol. 3, *Limnologia*, H. Lent, Ed. (Conselho Nacional de Pesquisas, Rio de Janeiro, 1967), p. 163.
4. J. F. Richey, E. Salati, H. Santos, R. H. Meade, 3rd Workshop—Carbon and Mineral Transport in Major World Rivers, Caracas, 25 March to 2 April 1984 (*Mitt. Geol. Palaeontol. Inst. Univ. Hamburg*, in press).
5. P. M. Fearnside, *Interciencia* **1** (No. 2), 82 (1982).
6. A. T. Hjelmfelt, *Proc. Am. Soc. Civ. Eng. J. Hydraulic Div.* **104**, 887 (1978).
7. V. E. Kousky and L. C. Molion, *Acta Amazonica*, in press.
8. E. Salati, A. Dall'Olio, E. Matsui, J. R. Gat, *Water Resour. Res.* **15**, 1250 (1979).
9. J. Marques, J. M. Santos, E. Salati, *Acta Amazonica* **9** (No. 4), 701 (1979).
10. J. Marques, E. Salati, J. M. Santos, *ibid.* **10** (No. 11), 133 (1980).
11. E. Salati and M. N. G. Ribeiro, *Supl. Acta Amazonica* **9** (No. 4), 14 (1979).
12. L. C. B. Molion, thesis, University of Wisconsin (1975); N. A. Villa Nova, E. Salati, E. Matsui, *Acta Amazonica* **6** (No. 2), 215 (1976); J. Marques, J. M. Santos, N. A. Villa Nova, E. Salati, *ibid.* **7** (No. 3), 355 (1977); J. Marques, E. Salati, J. M. Santos, *ibid.* **10** (No. 2), 357 (1980).
13. O. Fränzle, *Inst. Sci. Coop. (Tübingen) Appl. Sci. Develop.* **13**, 88 (1979).
14. H. Lettau, K. Lettau, L. C. B. Molion, *Mon. Weather Rev.* **107**, 227 (1979).
15. J. Marques, J. M. Santos, E. Salati, *Acta Amazonica* **9** (No. 4), 715 (1979).
16. P. R. Leopoldo, W. Franken, E. Matsui, in *Symposium on Change in the Amazon Basin, 44th International Congress of Americanists* (Univ. of Manchester Press, Manchester, England, in press).
17. P. R. Leopoldo, W. Franken, E. Salati, *Acta Amazonica* **12** (No. 2), 333 (1982); W. Franken, P. R. Leopoldo, E. Matsui, M. N. G. Ribeiro, *ibid.*, p. 327.
18. A. Dall'Olio, E. Salati, C. T. Azevedo, E. Matsui, *ibid.* **9** (No. 4), 675 (1979).
19. R. F. Stallard and J. M. Edmond, *J. Geophys. Res.* **86**, 9844 (1981).
20. E. Salati and P. B. Vose, *Ambio* **12**, 67 (1983).
21. E. Salati, T. Lovejoy, P. B. Vose, *Environmentalist* **3**, 67 (1983).
22. P. A. Sanchez, *Properties and Management of Soils in the Tropics* (Wiley, New York, 1976).
23. R. van der Weert, *Trop. Agric. (Trinidad)* **51**, 325 (1974).
24. C. E. Seubert, thesis, North Carolina State University (1975).
25. H. O. R. Schubart, *Acta Amazonica* **7** (No. 4), 559 (1977).
26. C. Charreau, *Agron. Trop. (Paris)* **27**, 905 (1972).
27. J. G. Daniel and A. Kulasingam, *Malay. For.* **37**, 152 (1974).
28. J. H. Troughton, "Natural isotopic variation in ecological studies" (report SP/5/1648 to the Government of Brazil, International Atomic Energy Agency, Vienna, 1980).
29. A. H. Gentry and J. López-Parodi, *Science* **210**, 1354 (1980).
30. C. F. Nordin and R. H. Meade, *ibid.* **215**, 426 (1982).
31. S. Kempe, *Mitt. Geol. Palaeontol. Inst. Univ. Hamburg* **52**, 231 (1982).
32. H. L. Penman, Technical Communication No. 53 (Commonwealth Agricultural Bureau, Farnham Royal, England, 1963).
33. H. C. Pereira, *Land Use and Water Resources in Temperate and Tropical Climates* (Cambridge Univ. Press, Cambridge, 1973).
34. P. R. Leopoldo, E. Matsui, E. Salati, W. Franken, M. N. G. Ribeiro, *Supl. Acta Amazonica* **12** (No. 3), 7 (1982).
35. P. M. Fearnside, in *Symposium on Change in the Amazon Basin, 44th International Congress of Americanists* (Univ. of Manchester Press, Manchester, England, in press).
36. E. F. Brünig, *Ambio* **6**, 187 (1977).
37. H. Klinge, *Biogeographica* **7**, 59 (1975).
38. E. J. Fittkau and H. Klinge, *Biotropica* **5**, 2 (1973).
39. G. de las Salas, *CONIF Ser. Tec.* **8** (Corporación Nacional de Investigaciones y Fomento Forestal, Bogota, Colombia, 1978).
40. H. W. Fassbender, in *Food and Agriculture Organization–Swedish International Development Agency Workshop, Meeting on Soil Management and Conservation in Latin America* (Food and Agriculture Organization, Rome, 1977), p. 11.
41. P. Artaxo Netto, C. Q. Orsini, M. H. Tabacknics, L. C. Bouéres, A. Leslie, *An. Acad. Bras. Cienc.* **54**, 299 (1982).
42. P. Artaxo Netto, C. Q. Orsini, L. C. Bouéres, A. Leslie, *Supl. Acta Amazonica* **12** (No. 3), 39 (1982).
43. D. R. Lawson and J. W. Winchester, *J. Geophys. Res.* **84**, 3723 (1979).
44. E. Salati, R. Sylvester-Bradley, R. L. Victoria, *Plant Soil* **67**, 367 (1982).
45. G. W. Schmidt, *Amazoniana* **3**, 208 (1972).
46. H. Sioli, *Naturwissenschaften* **56**, 248 (1969).
47. C. Jordan *et al.*, *Plant Soil* **67**, 325 (1982).
48. P. A. Sanchez, *ibid.*, p. 91.
49. B. Volkoff and C. C. Cerri, *Rev. Bras. Cienc. Solo* **5**, 15 (1981).
50. G. de las Salas and H. Folster, *Turrialba* **26**, 179 (1976).
51. J. Ewell, C. Berish, B. Brown, N. Price J. Raich, *J. Ecol.* **62**, 816 (1981).
52. W. L. F. Brinkman and J. C. do Nascimento, *Acta Amazonica* **3** (No. 2), 55 (1973).
53. E. A. S. Serrão, I. C. Falesi, J. B. da Veiga, J. F. Teixeira Neto, in *Produccion de Pastos en*

Suelos Acidos de los Trópicos, L. E. Tergas and P. A. Sanchez, Eds. (Centro Internacional de Agricultura Tropical, Cali, Colombia, 1979), p. 195.
54. R. H. Miller, J. J. Nicholaides, P. A. Sanchez, D. E. Bandy, in *Proceedings of the Regional Colloquium on Soil Organic Matter Studies*, C. C. Cerri, D. Athié, D. Sodrzeieski, Eds. (Companhia de Promoção de Pesquisa Científica e Tecnológica do Estado de São Paulo, PROMOCET, São Paulo, 1982), p. 105.
55. P. A. Sanchez, D. E. Bandy, J. H. Villachica, J. J. Nicholaides, *Science* **216**, 821 (1982).
56. P. Suarez de Castro and A. Rodriguez, *Fed. Nac. Cafeteros Colomb. Bol. Tec. 14* (1955).
57. J. E. Richey, *Mitt. Geol. Palaeontol. Inst. Univ. Hamburg* **52**, 365 (1982).
58. H. Sioli, *Amazoniana* **1**, 74 (1965).
59. R. J. Gibbs, *Geol. Soc. Am. Bull.* **78**, 1203 (1967).
60. ——, *Geochim. Cosmochim. Acta* **36**, 1061 (1972).
61. R. H. Meade, C. F. Nordin, W. F. Curtis, *An. 3rd Simp. Bras. Hidrol.* (Departamento Nacional de Água e Energia Elétrica, Brasília, 1979), vol. 2, p. 472.
62. R. F. Stallard, thesis, Massachusetts Institute of Technology (1980).
63. N. A. Villa Nova and E. Salati, in *Simpósio Anual da Academia de Ciências do Estado de São Paulo* (Anais 6, ACIESP, São Paulo, 1977), p. 27.
64. M. N. G. Ribeiro, E. Salati, N. A. Villa Nova, C. G. B. Demetrio, *Acta Amazonica* **12** (No. 2), 339 (1982).
65. J. S. Oguntoynbo, *Q. J. R. Meteorol. Soc.* **96**, 430 (1970); R. Pinker, O. B. Thompson, R. F. Eck, *ibid.* **106**, 551 (1980).
66. R. E. Dickinson, *Studies in Third World Societies* (William and Mary College, Williamsburg, Va., 1981), vol. 14, p. 411.
67. L. C. B. Molion and J. J. U. Bentancurt, in *Woodpower, New Perspectives on Forest Usage*, J. J. Talbot and W. Swanson, Eds. (Pergamon, Oxford, 1981), p. 239.
68. S. C. Snedaker, thesis, University of Florida (1970).
69. R. K. Cunningham, *J. Soil Sci.* **14**, 334 (1963).
70. *Tech. Rep. Natl. Environ. Satellite Center Environ. Sci. Services Admin. 51* (1974), p. 4.
71. G. L. Potter, H. W. Ellsaesser, M. C. MacCracken, F. M. Luther, *Nature (London)* **258**, 697 (1975).
72. G. L. Potter, H. W. Ellsaesser, M. C. MacCracken, J. S. Ellis, *ibid.* **291**, 47 (1981).
73. A. Henderson-Sellers, in *Proceedings of the 6th Annual Climate Diagnostics Workshop* (National Oceanic and Atmospheric Administration, Washington, D.C., 1981), p. 135.
74. J. Charney, W. J. Quirk, S. H. Chow, J. Kornfield, *J. Atmos. Sci.* **34**, 1366 (1977).
75. "Alteração da cobertura vegetal natural da região Amazônica" (Programa de Monitoramento da Cobertura Florestal do Brasil, Brasilia, 1982).
76. R. C. Newell, in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 457.
77. M. F. Wilson and A. Henderson-Sellers, in *Hydrology of Humid Tropical Regions*, R. Keller, Ed. (Publication 140, International Association of Hydrological Sciences, Hamburg, 1983), p. 273.
78. A. P. M. Galvão, C. A. Ferreira, L. B. Teixeira, *J. Inst. Pesqui. Estud. Florestais (Piracicaba)* **19**, 47 (1979).
79. P. T. Alvim, in *Extinction Is Forever*, G. T. Prance and T. S. Elias, Eds. (New York Botanical Garden, New York, 1977), p. 347; B. Amilcar, *Rev. Bras. Tecnol.* **12** (No. 4), 17 (1981); E. Eckholm, "Disappearing species: the social challenge" (Worldwatch Paper 22, Worldwatch Institute, Washington, D.C., 1978); N. Myers, *Science* **193**, 198 (1976); R. B. Nigh and J. D. Nations, *Bull. At. Sci.* **36**, 12 (1980).
80. J. C. de Melo Carvalho, *Companhia Vale Rio Doce Rev.* **2** (No. 4) (special edition) (1981).
81. E. Salati, P. I. S. Braga, R. Figliulo, Eds., *Supl. Acta Amazonica* **9** (No. 4), 5 (1979).
82. A. Chauvel, *ibid.* **12** (No. 3), 47 (1982).
83. I. C. Falesi, *Empresa Bras. Pesqui. Agropecu. (EMBRAPA) Bol. Tec. No. 193* (1976).

Genetic Screening: Marvel or Menace?

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Is genetic screening a marvel about to free us from the scourge of genetic disease, or a menace about to invade our privacy and determine who may reproduce?

Genetic screening may be defined as a systematic search in a population for persons of certain genotypes. The usual purpose is to detect persons who themselves are at risk or whose offspring are at risk for genetic diseases or genetically determined susceptibilities to environmental agents (*1*). When an individual is diagnosed as having a genetic condition, the testing of relatives may be recommended. This "retrospective screening" differs from the screening of individuals without known affected relatives (prospective screening). Genetic screening may be undertaken also for research purposes unrelated to disease or the improvement of health. Retrospective screening and screening for research purposes will not be further considered here.

Genetic screening differs from nongenetic health screening in at least three important ways. First, whereas in both types of screening, identification of persons at risk may lead to the identification of others at risk, in the case of ordinary health screening the connection is often by physical proximity (contact) whereas in genetic screening it is by genetic proximity (kinship). Second, whereas in other forms of health screening the concern is about the subject being screened, in genetic screening the concern is often about the subject's offspring. Third, genetic screening carries an inherent risk of impairing self-image and perceived suitability as a marriage partner or parent.

Types of Genetic Screening

There are three principal types of genetic screening. Newborn screening seeks disease in the newborn. Fetal (prenatal) screening seeks disease in the fetus. Carrier screening seeks heterozygotes for genes for serious recessive disease. The three types have, respectively, a long established, a recently established, and a yet to be established place in health care.

Newborn Screening

Newborn screening has focused largely on the detection of inborn errors of metabolism. An inborn error of metabolism is an inherited biochemical defect, classically a deficiency of an intracellular enzyme. Such deficiencies cause disease due either to the accumulation of the enzyme's reactant or its metabolites or to a deficiency of the enzyme's product.

Phenylketonuria (PKU) was the first condition for which newborn screening was widely adopted (*2*). Mass screening was feasible, despite the disease's low incidence by public health standards (1 in 11,500) (*3*), because of the discovery, by Guthrie in 1961 (*4*), of a bacterial growth inhibition assay for measuring blood phenylalanine. Before a newborn is discharged from the hospital, a sample of its blood is spotted onto filter paper and mailed to a regional laboratory (*5*). Despite the fact that most states made newborn screening for PKU mandatory before methods for diagnosis and treatment of the disease were firmly established, newborn screening for PKU remains a major triumph of genetic screening (*6*). A low phenylalanine diet begun in the first few weeks of life prevents marked mental retardation in affected children.

Phenylketonuria, initially thought to be a single disease, illustrates the phenomenon of genetic heterogeneity. High concentrations of phenylalanine in the blood of a newborn may have multiple genetic and developmental causes. In

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