structure and topography of the terrain, palms being a prevalent feature in Amazonian forests. Luizão and Schubart show the importance of litter decomposition and of the soil organisms as decomposers for the recycling of nutrients and thus for the maintenance of the forest, while Rylands gives a detailed account of monkeys as consumers of the living biomass in the forest canopy. Walker, finally, integrates the biology of streams into the general ecological process of forest dynamics.

It is hoped that the review conveys one aspect in particular with penetrating clarity: namely, that of the mutual interdependence of all the described processes and patterns from which the multiple dangers to and fragility of this gigantic ecosystem directly follow. The consideration of this balance is indispensible for any land use by man in the Amazon Basin.

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Towards a water balance in the Central Amazonian region

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Key words. Hydrological cycle; Amazon River; evapotranspiration; canopy interception; water budget; precipitation; Amazon Basin; deforestation effects.

1. Introduction

The possible effect of the Amazonian forest ecosystem on the regional, or even on the global, climate, is a subject discussed with much polemical ado.

Until the 1960s the Amazonian forest cover remained essentially intact[4]. However, with the construction of roads in the 70s colonization, accompanied by deforestation, set in with ever-increasing speed. Under the auspices of the 'Instituto Nacional de Colonização e Reforma Agrária', the government alone removes an average of 25,000 km^2 of forest per year[50].

As a result of this process, national and international concern has intensified. In the absence of hard scientific data, and nurtured by conjecture and hypotheses only, the discussion has acquired a rather unrealistic and perhaps even polemical tenor, and contradictory views are defended with equal conviction.

Thus, some authors claim that the energy liberated by the condensation of water vapors from the Amazon Basin, which is transported in the higher atmospheric strata to the polar regions, represents an important contribution to the thermal equilibrium of the earth[35]. If this were proven to be true, the deforestation of this region would result in a higher temperature contrast between polar and more central latitudes of the globe.

Others hypothesize that even complete deforestation would have little global impact. Sellers[47] estimates that the effect would merely be a reduction of the annual rainfall in Amazonia by 250 mm, and, on the other hand, the arid Brazilian Northeast would benefit from increased precipitation. Conclusions of global irrelevance have also issued from the Centre for Informatics, Goddard Institute, New York, which is considered to be one of the most sophisticated agencies for simulation prognostication. In this model, the climatological parameters of the forest, such as surface temperature, evapotranspiration, light reflection, etc. were replaced by the respective values for tropical pastures. The model[51], however, omits important factors such as the release of CO_2 by the burning of the forest; this is one of the major preoccupations of climatologists, because it might lead to higher global temperatures and thus could even cause partial melting of the polar ice caps[47]. As for regional effects, the Goddard futurologists admit that pastures would retain less rainwater and that, therefore, erosion would intensify and cause an equivalent increase of sediments in rivers, and that this, in turn, could endanger the plankton and the entire aquatic fauna[51].

Fortunately, though, matters have moved beyond mere conjecture and dispute. National and international agencies have cooperated in setting up a number of research programs on the interaction between vegetation and atmosphere throughout the northern Brazilian states and through the Amazon Basin as a whole, including the neighboring countries (fig. 1). For example, the Instituto Nacional de Pesquisas da Amazônia (INPA), the Centro de Energia Nuclear na Agricultura (CENA), the Instituto Nacional de Pesquisas Espaciais (INPE), ORSTOM (France), the American States Organization (OEA), the International Atomic Energy Agency (IAEA), and the IVIC (Venezuela-San Carlos), are only a few of them. Some results of the OEA-project, at Model Basin, are summarized by Walker and Franken[53].

However, in view of the enormous problems, that would arise from a possible destabilization of the Amazonian

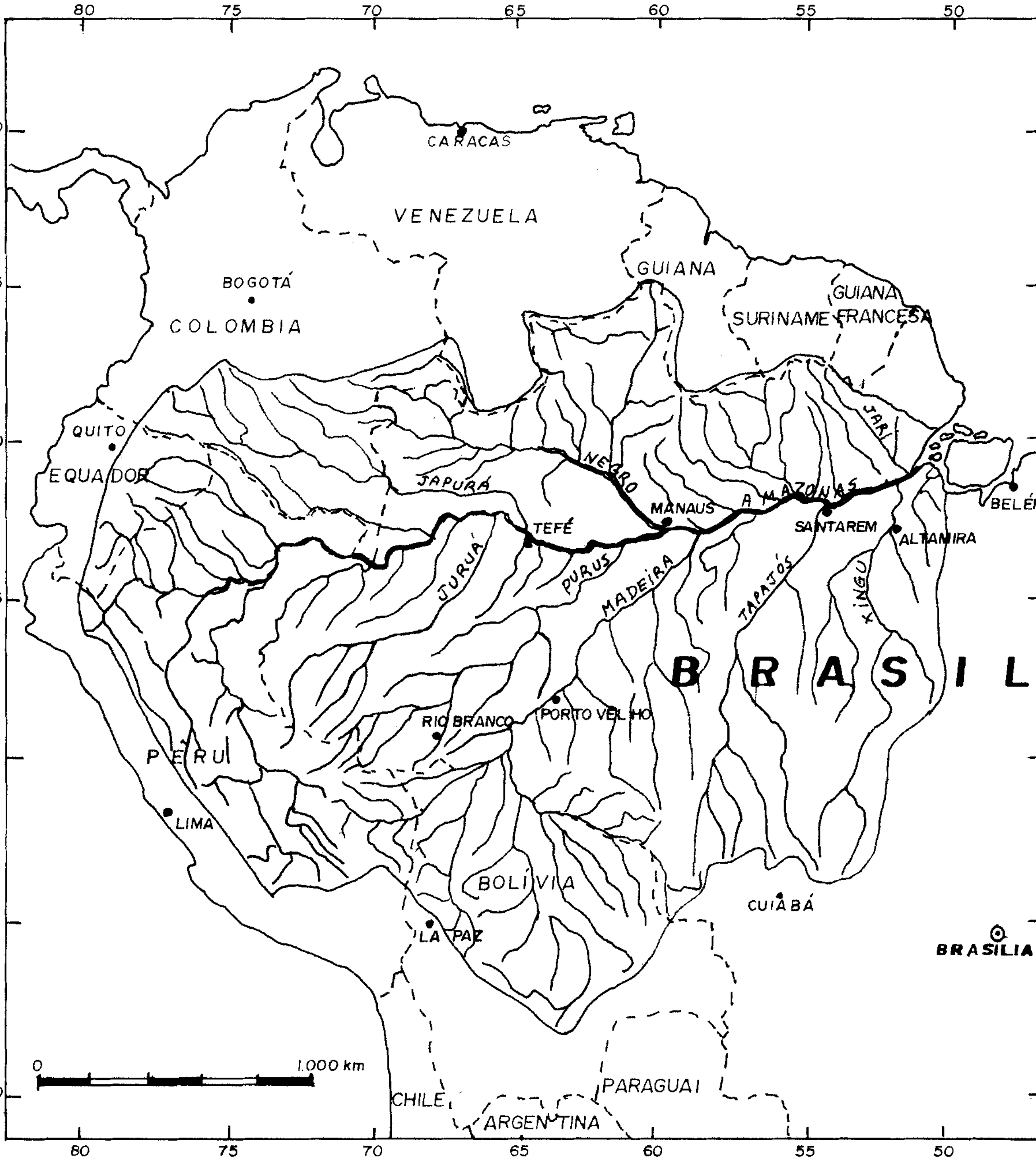

Figure 1. Amazon Basin.

ecosystem, these efforts must be considered as a modest beginning and as an incentive for continued research.

II. General aspects of the Amazon Basin

The Amazon Basin, with its roughly 5.8×10^6 km^2, drains approximately one third of the South American continent, and 45% (namely 3.8×10^6 km^2) of Brazil alone. This does not include the independent basin of the Tocantins-Araguaia (1.0×10^6 km^2) which is generally, but erroneously, included in Amazonian estimates.

The Amazon Basin is surrounded by three major geological formations: firstly the Andean Cordilhera with its 5000 m peaks; secondly, the massive Guinean Shield which separates it to the north from the basin of the Orinoco, and includes Brazil's highest mountain ranges (Pico da Neblina, 3014 m); and thirdly, to the south by the shield of the Brazilian Planalto with modest altitudes ($\sim$ 700 m), which forms the limit towards the basin of the Paraná. These two ancient, precambrian shields form essentially a semi-circle which surrounds a vast plain of tertiary sediments. This plain falls off, rather abruptly, into the so-called 'várzeas' and 'igapós' (inundation forests of white and black water respectively), which accompany the main water courses.

The main channel of the basin is the 'Amazonas-Ucaiali-Urubamba' course, originating at 10° south in the Peruvian Andes at an altitude of about 4000 m. The total length of this water course is 6577 km and is exceeded only by that of the river Nile.

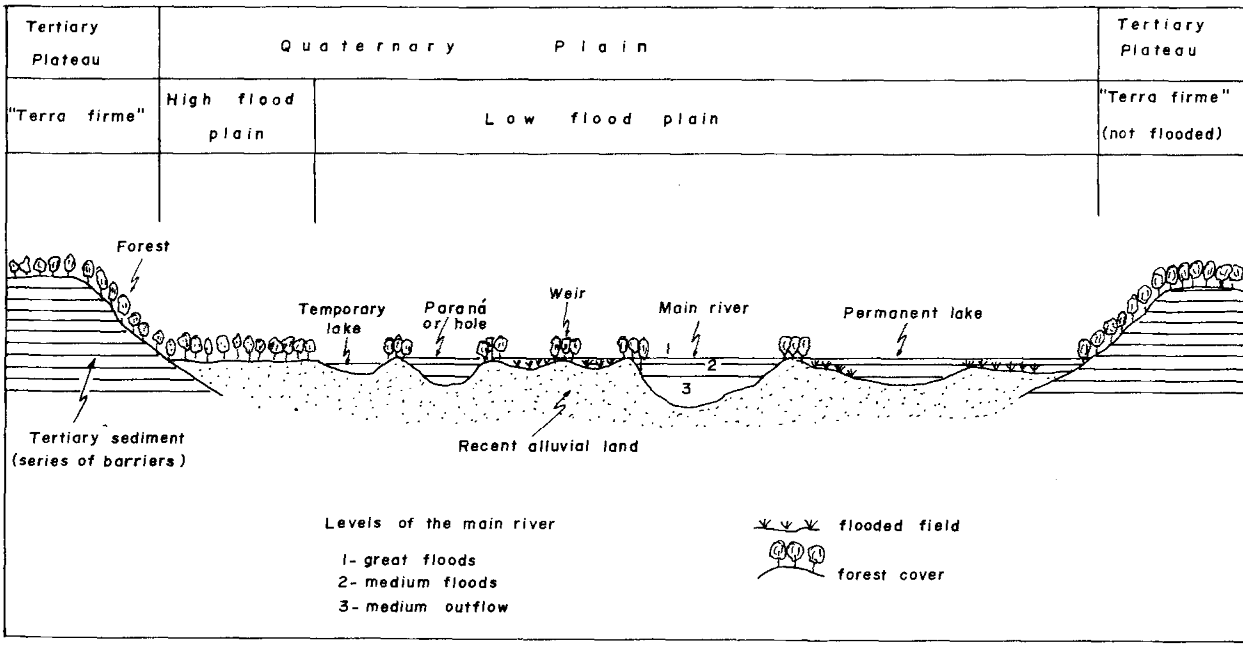

Figure 2. Typical section of a sediment transporting Amazon river.

As a mountain river with steep declivity it runs initially south-north until 5° south, then it turns in an west-easterly direction towards the Atlantic Ocean. In this part declivity is minimal. From the Brazilian frontier city Tabatinga to its mouth at Belém, that is for a distance of roughly 3000 km, the river bed falls only 60 m; this gives an average declivity of 2 cm/km. This led and still leads to meander-formation (figs 2 and 3) and to annual inundations of the lower-situated forests with a water depth of 7–9 m.

As the southern tributaries of the Amazon are, on the whole, longer than their northern counterparts, because the Amazon itself does not run in the center of its basin, but somewhat to the north, the water volume received from the southern hemisphere is larger than the one from the northern affluents. Hence, the inundations caused by the respective hemispheric summer rains are primarily determined by the southern tributaries. Thereby the rivers of Andean origin are especially important because of their additional input of melted snow.

The Amazonian drainage system with its thousand and more tributaries is one of the world's densest; it includes about 20,000 km of navigable rivers and contributes 15–20% of the world's total fresh water discharge into the Atlantic Ocean[25,29]. According to Oltmann et al.[34] and confirmed by more recent estimates[38] the average discharge is $\sim 175{,}000\ m^3/s$, this is five times the value for the Congo, and adds up to $5.5 \times 10^{12}\ m^3/y$. The seasonal variations are, however, massive; the annual, maximum difference in water levels in Manaus between the lowest (end of Oct/Nov) and highest (end of May/June) values is 7–12 m (fig. 4).

With regard to sediment transport three types of rivers can be distinguished, namely those with white, black and

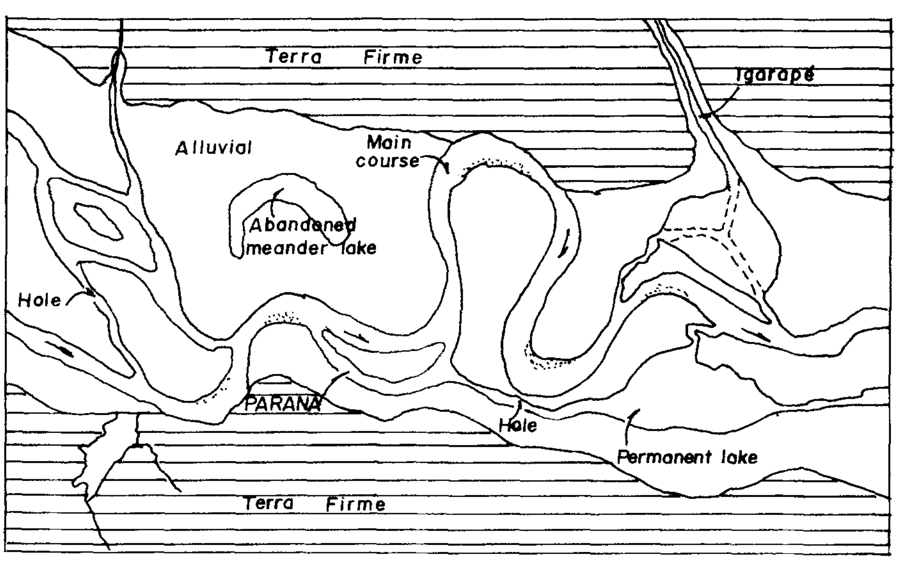

Figure 3. Characterization of the main draining elements of the Amazon flood-plain.

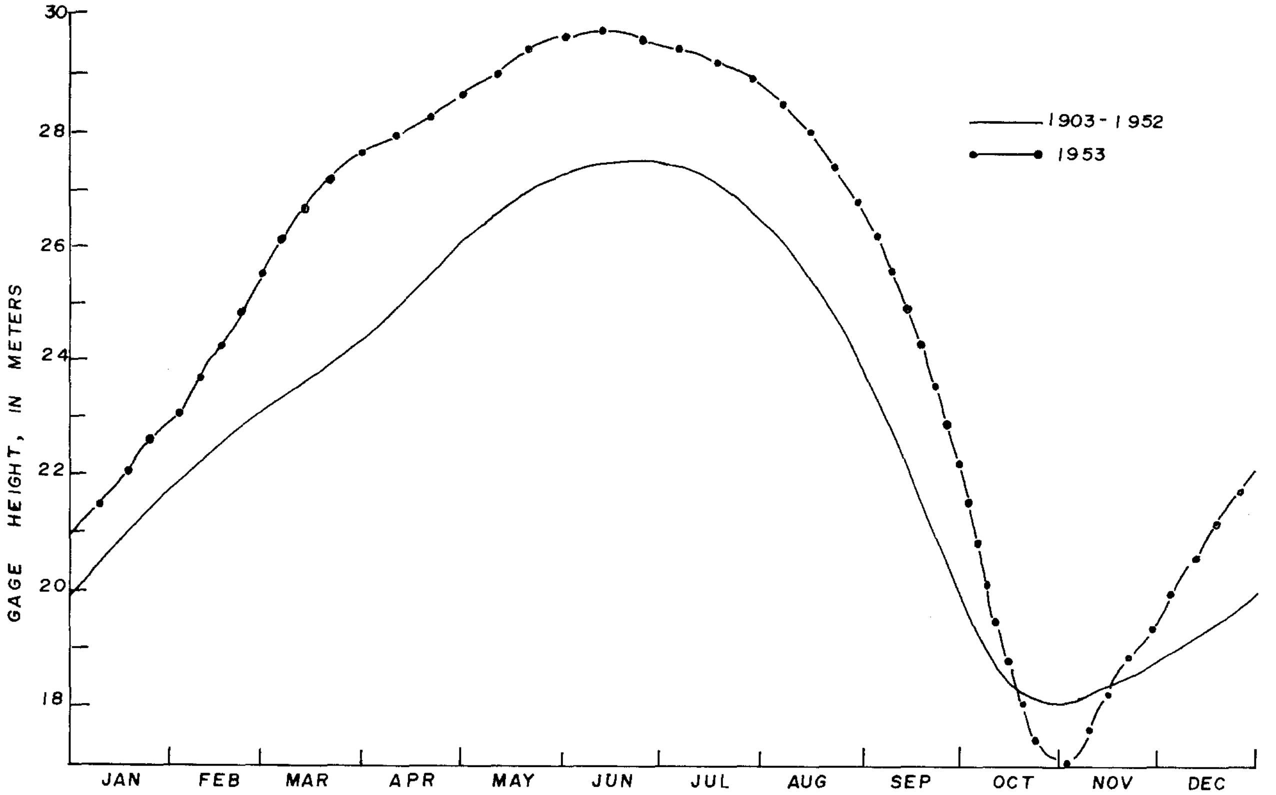

Figure 4. Gage height above sea level, of Amazon River, near Manaus, in the periods 1903–1952 and 1953[34].

clear water. Rivers with white water, such as the Amazon itself, the Purus, Madeira and Jurua, originate in the Andes or at least in the Andean piedmont, where erosion is intensive[9,10]. The high level of suspended sediments leads to the color of light, milky coffee under a sunny sky; under a rainy cloud cover these rivers look virtually white. The pH ranges from 6.5–7.0 and conductivity from 60–70 $\mu S_{20}/cm$[22]. These relatively fertile waters harbor the world's richest fish fauna, with an estimated 2000 species [24,31]. From the Congo, second in this respect, about 1000 species are described.The Amazon's high flood plain (várzea) with its annual inundations is thus regularly fertilized and is a region of real agricultural potential (fig. 2).

Clear water rivers take their origin in the ancient shield formations which have long since been stripped of their nutrient minerals; thus they are relatively infertile. Low declivity and forest cover prevent erosion. The level of suspended sediments is therefore usually negligible – whence their name. The region of the head waters of the Tapajos, Xingu and of some smaller rivers, though, is characterized by 'cerrado', that is dry savannah-type tree vegetation.

Like the clear water rivers, black rivers (Rio Negro) originate in geologically old, nutrient-poor formation of modest altitude. They, too, carry a negligible quantity of suspended sediment. The 'black' color (light-orange-brown in transmitted light) is due to dissolved humic and fulvic acids[48], the leftovers of incomplete decomposition of organic forest litter. Black rivers are truly black in incident light and under stormy clouds, but they mirror the light blue of a clear sky. Black water rivers are acid (pH 4–5) and their conductivity ranges from 8–15 $\mu S_{20}/cm$[15].

The vegetative cover of the greater part of the Amazon Basin is an as yet almost unbroken carpet of dense, equatorial rain forest which constitutes 42% of Brazil, for instance, ($\sim 3.6 \times 10^6$ km^2). This forest, though, far exceeds the basin proper. It occupies almost the entire northern part of South America, thus including the Guyanas, Surinam, East and South Venezuela, Southeast and South Colombia, the easterly parts of Ecuador and Peru, and North Bolivia. It also covers the eastern slopes of the Peruvian, Equadorian and Colombian Andes.

Despite its superficially homogeneous appearance, this forest is composed of distinct vegetation types[12] with a preponderance of the 'terra-firme' forest (never inundated by the annually raised water of the big rivers). In Brazil alone this type of forest covers approximately 3.4×10^6 km^2.

The soils of this vegetation are, on the whole, poor. However, the tropical combination of high temperature and high precipitation allows for intense photosynthesis. The nutrients necessary for this process are essentially tied up in the biomass of this luxuriant forest and are continuously re-cycled via decomposition and reabsorption. Small losses are compensated by the mineral input in the rain[7,44,46,53].

III. Precipitation

1. General pattern. As seen from figure 5 and table 1, precipitation is far from homogeneous. There is considerable variation of annual totals from place to place and of

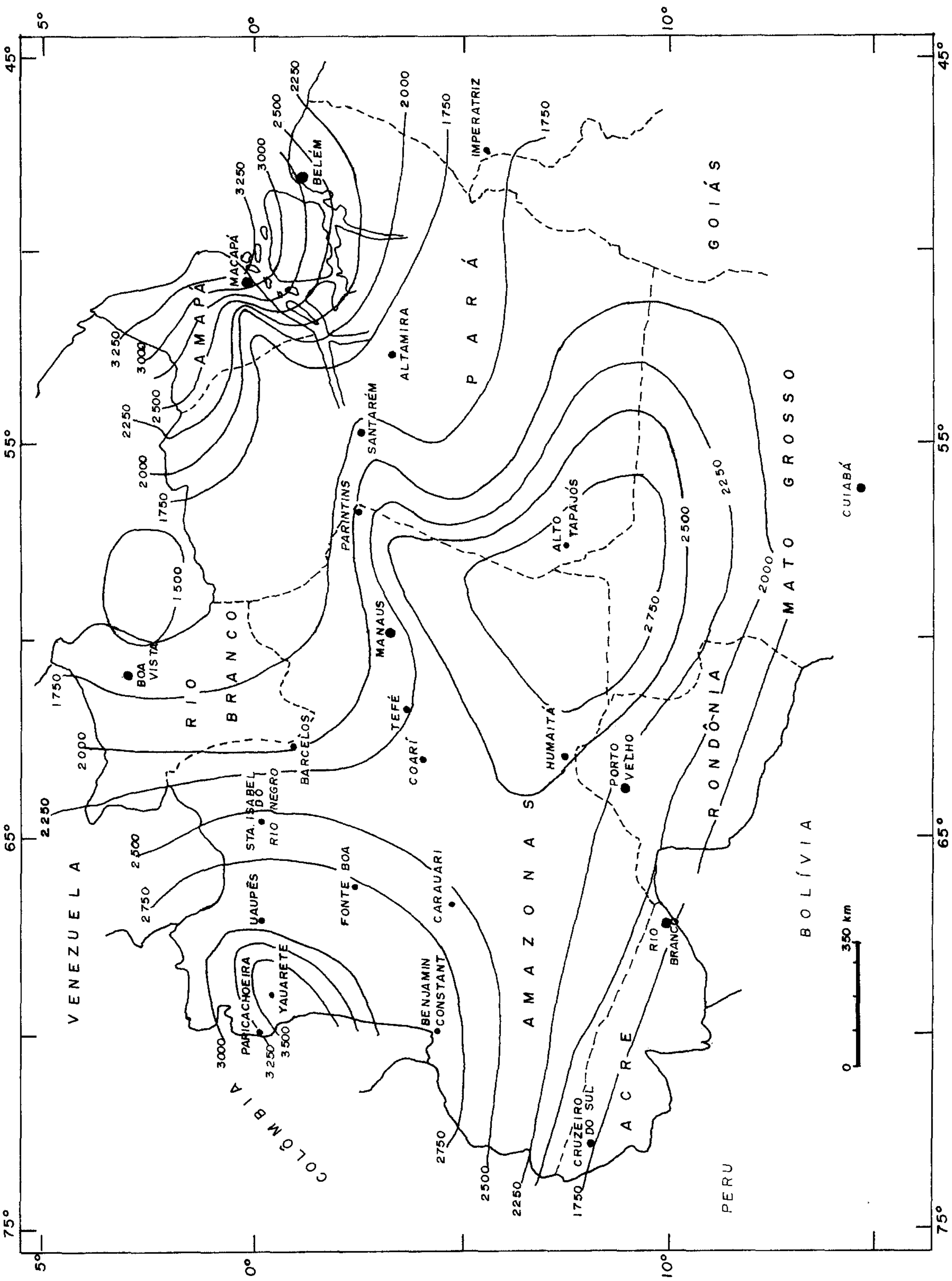

Figure 5. Annual isohyets in Brazilian portion, after Nimer[32].

monthly means throughout the year. The annual total exceeds 3000 mm/y near the Atlantic coast and in the west towards the Columbian border; in the central basin it is more moderate (2000–2500 mm/y). In general there is a relatively drier period from July to October, but there are exceptions, expecially in the regions of precipitation maxima.

The major flow of atmospheric water vapor into the Amazon Basin comes from the northern hemisphere with the easterly trade winds, whence the extremely high precipitation near the Atlantic coast. However, as the winds penetrate inland, the contribution of rainfall due to the forest's evapotranspiration becomes relatively ever more important (see next chapters).

Table 1. Monthly average precipitation as a function of site and period of observation (in mm)

Site	Observation period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
Altamira	1961–1973	223	241	344	269	204	95	81	22	22	33	46	130	1710
Alto Tapajos	1931–1960	408	375	434	285	128	26	11	33	138	235	315	329	2717
Barcelos	1931–1960	172	145	174	256	276	234	169	118	105	118	111	125	1999
Benjamin Constant	1951–1960	340	280	350	280	210	140	120	140	200	220	250	280	1810
Carauari	1961–1977	330	173	227	336	245	152	89	157	186	230	310	269	2704
Coari	1931–1960	315	274	280	283	226	134	88	75	99	158	188	222	2347
Fonte Boa	1931–1960	298	237	278	336	314	238	175	149	150	194	186	247	2802
Humaitá	1962–1973	261	277	319	250	163	54	21	60	107	184	255	283	2234
Yayaretê	1931–1960	259	246	295	363	389	356	350	278	266	237	227	237	3503
Macapá	1968–1973	256	325	394	291	349	208	173	99	56	15	66	147	2379
Manaus	1931–1960	276	277	301	287	193	98	61	41	62	112	165	228	2101
Pari Cachoaeira	1965–1973	260	199	323	281	403	327	359	259	187	224	171	220	3213
Parintins	1961–1973	250	279	324	356	346	200	112	88	41	77	142	161	2376
Porto Velho	1961–1973	265	307	283	254	134	39	27	42	111	186	222	288	2158
Rio Branco	1969–1973	202	252	227	175	99	31	28	48	88	154	226	236	1766
Santa Isabel do Rio Negro	1966–1973	211	179	282	291	306	243	199	197	168	126	180	174	2556
Santarém	1931–1960	179	275	358	362	293	174	112	50	39	46	85	123	2096
Tefé	1970–1973	220	213	289	299	229	166	221	102	117	128	177	160	2321
Uaupês	1931–1960	274	250	285	267	317	250	246	195	148	173	202	305	2912
Belém	1931–1960	318	407	436	382	266	165	161	116	120	105	90	197	2763
Imperatriz	1931–1960	241	256	309	219	89	19	10	6	40	92	152	198	1631

According to Kousky's[18] suggestions the coastal maximum of precipitation would result from might convergence between the incoming trade winds and the land breeze close to the coast. Reduced rainfall further inland (~ 500 km from the Atlantic coast) would be due to reduced thermal contrast, and hence to reduced diurnal convection. However, the high annual rainfall in Central Amazonia cannot be explained merely by the formation of convection cells.

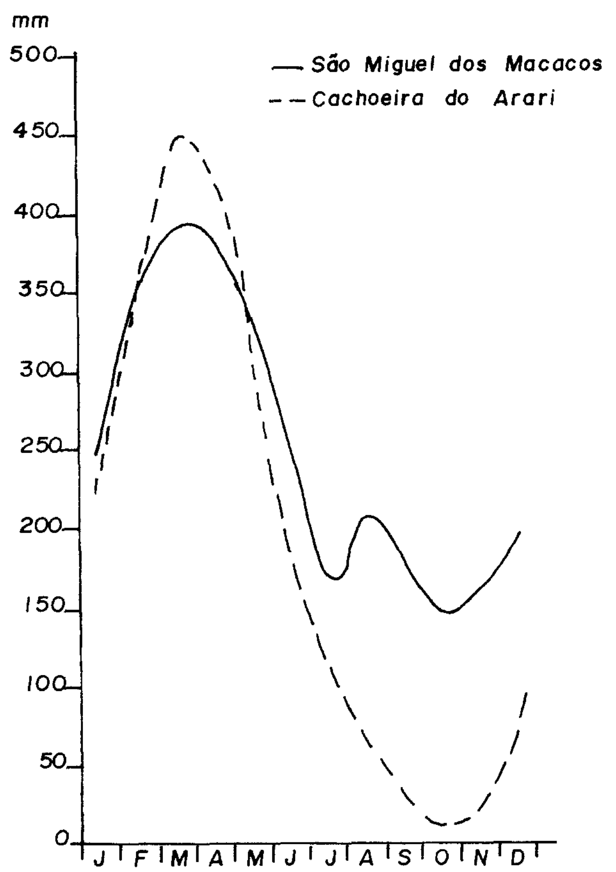

Figure 6. Rainfall distribution at São Miguel dos Macacos and Cachoeira do Arari, on Marajó Island.

Thus, Salati and Vose[41] observed that different patterns of rainfall are a function of interaction between the Intertropical Convergence Zone and the Equatorial Atlantic Air Mass in the eastern region, and, in the westernmost region, a function of the presence of the Equatorial Continental Air Mass.

In the center of the basin the seasonal regime of rainfall is largely determined by the expansion of the continental air mass in summer and its contraction in winter.

Radio sondes and isotope analysis have been used to study the movement of water vapor in the Amazonian region[26]. It was found that this region exports part of its vapor to the Chaco Paraguaio and to Central Brazil, mainly in March and December, but to some extent the year round.

This is important because changes in the water regime of the Amazon Basin will thus have direct consequences for the rainfall in the Central Brazilian Plateau, which, in turn, feeds the head regions of the hydrographic basins of the Paraná, the Paraguai, and of some lesser rivers. This export of vapor, apparently, is due to local conditions. According to aerial studies and examination of satellite images[40] there seems to be no major influx of air from the north that could cause the dislocation of Amazonian water vapor to the south.

In the east, the Andes form a natural barrier that prevents water vapor from leaving the Amazonian region in this direction. This leads to precipitation values that may exceed 5000 mm/y on their eastern slopes.

Opinions about the relative importance of evapotranspiration by the forest for the magnitude of precipitation are conflicting. Lettau et al.[22] hold the view that it is unimportant and, consequently, that activities such as land drainage and construction of large reservoirs, accompanied by deforestation, have little impact on local rainfall. This seems unlikely though. Salati and Vose[41] argue that the horseshoe-shaped formation of the Amazon Basin, with its major influx of vapor brought by the

Experientia 43 (1987), Birkhäuser Verlag, CH-4010 Basel/Switzerland

Table 2. Ranges of rainfall events in the Barro Branco watershed

Ranges of rainfall (mm)	Number of events	% n	Amount (mm/years)	% mm
< 4.9	328	75.1	392.4	19.0
5.0– 9.9	49	11.2	352.2	17.0
10.0–19.9	40	9.2	577.7	27.9
20.0–29.9	10	2.3	240.6	11.6
30.0–39.9	2	0.4	68.0	3.3
40.0–49.9	3	0.7	130.7	6.3
> 50.0	5	1.1	308.5	14.9

Table 3. Rainfall intensities observed in the Barro Branco watershed, and their classification

Rainfall intensity ($mm \cdot h^{-1}$)	Number of events	% n	mm	% mm	Classification
< 4.9	241	57.9	543.5	27.0	Light rains
5.0– 9.9	91	21.9	550.6	27.4	Heavy rains
10.0–14.9	40	9.6	493.8	24.5	Heavy rains
15.0–19.9	22	5.3	140.1	7.0	Heavy rains
> 20.0	22	5.3	283.9	14.1	Storms
Total	416	100.0	2011.9	100.0	

Table 4. Rainfall duration in the Barro Branco watershed

Duration (min)	Number of events	% n	mm	% mm
< 60	310	74.5	684.9	34.0
61–120	51	12.3	359.5	17.9
121–180	18	4.3	194.9	9.7
> 180	37	8.9	772.6	38.4
Total	416	100.0	2011.0	100.0

trade winds from the east, which eventually leaves the system again with the river's efflux in the same direction, lead one to anticipate that recycling via evapotranspiration and local precipitation will play a major role.

In this respect data from the 'Ilha de Marajó' (region of the Amazon estuaries) are relevant. This island of ~ 50,000 km^2 is partly covered by rain forest and partly by natural grassland. Between these two parts there is a mean difference in precipitation of ~ 700 mm/y (3000 mm over forest; 2300 mm over grassland); the grassland, moreover, experiences a short, but marked, dry season, whereas precipitation is high the year round over the forested areas (fig. 6).

2. Detailed patterns of precipitation. Franken and Leopoldo[6] analyzed the detailed pattern of one year's rainfall in INPA's forest reserve Ducke (tables 2, 3 and 4). The total of 437 rainfall events mounted up to 2070 mm; statistically, this value agrees with the annual mean of 2481 mm/y of the previous ten years measured in this forest station. Rainfall events with 10–19.9 mm contribute the highest fraction of the annual total[6]; 73% of precipitation falls in relatively short, heavy rains and storms. This suggests that the forest plays an important role in protecting the soil against erosion.

IV. Interception by the canopy

Intercepted rain is the part of the incoming rain that is directly evaporated by the foliage of the canopy without ever hitting the ground. As Franken et al.[5] showed by their studies in the 'Bacia Modelo', this process plays a considerable role in the maintenance of the water balance in the Amazon Basin; in fact, it includes roughly 20% of total precipitation (table 5).

Total rainfall (P_T) over the forest canopy splits up into three distinct parts: Interception (I), rain falling and dripping through the canopy (P_I = internal precipitation or throughfall or simply drip) and water running to the ground along the stems (and lianas) (E_T = stem flow). All, except interception, can be directly measured; hence I can be calculated:

$$I = P_T - (E_T + P_I)$$

The expression ($E_T + T_I$) stands for 'effective precipitation' and represents the part of the rain that reaches the soil under the vegetation cover.

For the observation of the total rainfall (table 5) 3 rain gauges were installed in a clearing adjacent to the Bacia Modelo, for P_I, 30 rain gauges inside the forest were used, and E_t was measured with 37 samplers, after Lima[23]. The experiment was carried out from 18.4.80 to 14.5.81.

Detailed analysis of the data summarized in table 5 shows that interception depends on the intensity of rain. A higher fraction evaporates if rains are light, namely I = 35% of rains below 10 mm/event and 12.6% of rains above 10 mm/event.

Similar measurements were taken in the forest reserve Ducke where the watershed of the stream 'Barro Branco' was under study. Of this study area 95% is under primary forest, 2% under an experimental rubber plantation and 3% is clearing. As stemflow was collected for chemical analysis, no data on its volume are available. Using the estimate of the Bacia Modelo (0.3%), Interception (I) in the Barro Branco basin amounts to 19% of a total precipitation of 2076 mm.

Estimates in the region of the upper Rio Negro, in Venezuela, show the following values: Total precipitation = 3634 mm/y, throughfall = 87%, stem flow = 8%, interception = 5%[14].

The discrepancy of values between the two regions may be the result of the extremely high total rainfall, with an atmosphere practically always near saturation. The difference in stemflow must be attributed either to different tree morphology or to different methodology.

For comparison, the P_I data from a sugar cane field in São Paulo State may be interesting (fig. 7)[19].

V. The water budget

In view of the enormous size and complexity of the Amazon Basin it is difficult to arrive at a realistic water budget. As a first approximation, total rainfall over the re-

Table 5. Subdivision of the total rainfall into leaf drip, stemflow and interception in Bacia Modelo watershed

Observation	mm	%
Total rainfall (P_T)	1.705	100.0
Leaf drip P_I	1.337	78.4
Stemflow E_T	6	0.3
Effective precip. ($E_T + P_I$)	1.344	78.8
Interception I	362	21.2

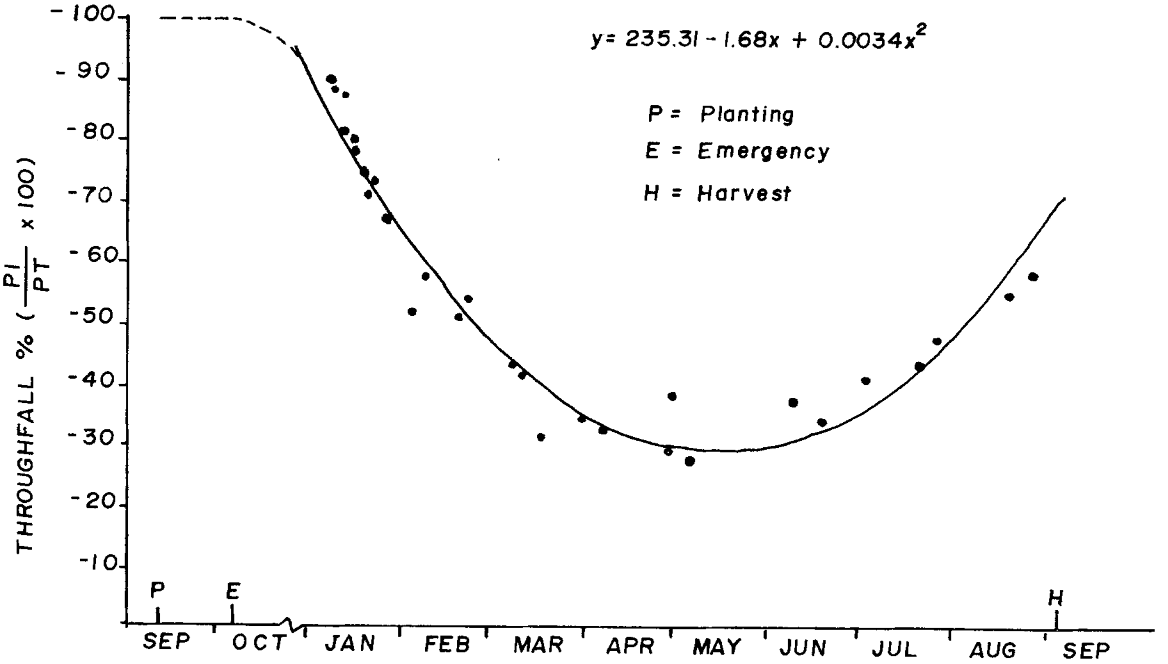

Figure 7. Regression curve for the percent values of the through fall in function of the crop cycle.

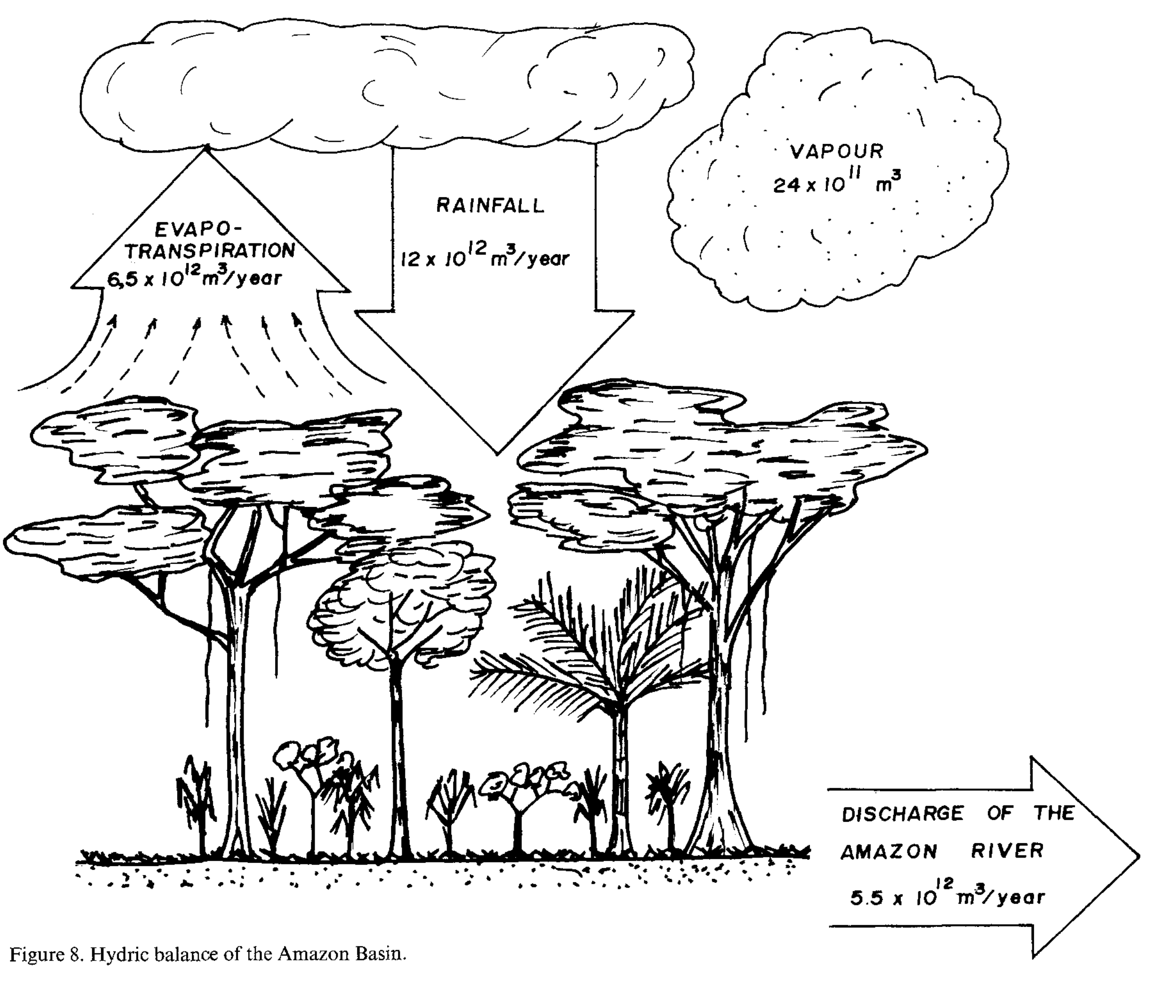

Figure 8. Hydric balance of the Amazon Basin.

gion of the basin is estimated at 12.0×10^{12} m^3/y, of which only 5.52×10^{12} m^3/y are received as runoff by the Atlantic Ocean. The difference (6.48×10^{12} m^3/y = 54%) must be attributed to the process of evapotranspiration by the vegetation cover (fig. 8)[52]. This includes interception, as well as evaporation by the leaves of the water that transports the nutrients from the roots to the canopy and, into the bargain, serves to cool the leaf surface during the day time.

With the intensified colonization in the seventies, which opened up roads and initiated the use of land for agriculture and cattle breeding, there arose the necessity for obtaining reliable data on the hydrological components of the system, because profound changes in the water regime must be expected as a result of deforestation.

During the last decade a number of independent projects have produced data by different methods in hydrographic basins of microscopic and macroscopic scale. These results are summarized in table 6.

Although same reservations are necessary, because of the variation in methodology and in size and place of regions assessed, we may draw the following major conclusions: The lowest estimate of evapotranspiration is 43%, corresponding to 1000 mm/y; the overall mean of the real values is 59% (= 1407 mm/y). Assuming that direct evaporation from the forest floor is zero and mean interception 22%, transpiration by the forest amounts to 46% (= 1097 mm/y).

The unavoidable conclusion is that the forest must play an important role in the maintenance of the Amazonian water balance: the equivalent of an inland sea of 1.1 m depth extending over roughly 4.0×10^6 km^2 is evaporated annually by the Amazon forest.

VI. Evidence for water recycling

The 50–75% of precipitation that returns to the atmosphere by evapotranspiration amounts to roughly 6.48×10^{12} tons of vapor produced annually by the forest of the Amazon Basin.

As a next step one needs to know whether this vapor is recycled via renewed precipitation in the basin itself or whether it is exported to other regions. As long term, mean values of the water budget point to a dynamic equilibrium between forest and atmosphere, exportation would imply compensating importation of vapor.

According to a study by Mollion[30], one part of the locally produced vapor is recycled relatively rapidly in the lower layers of the atmosphere, while another part remains for longer periods in the upper strata; in addition, the two strata are linked by energetic interactions.

Salati[42] presented several hypotheses on the possible fate of the vapor produced by the forest.

Firstly, Amazonian vapor could join the oceans and be exchanged with primary vapor from the oceans. As the Andes form a natural barrier, 4000–5000 m high, vapor exchange with the Pacific ocean is minimal, as is shown on the one hand by the negligible portion of marine Cl^- in the precipitation on the Eastern Andean slopes and in the upper Amazonian river waters[41] and, on the other hand, by the extremely high values for rainfall on the Eastern Andean slopes, which result from the condensation of vapor arriving from the more westerly regions of the basin.

Secondly[42], the Amazon Basin could export vapor towards the Planalto in the south and towards the Guyana Shield in the north, and would receive Atlantic vapor in return.

Thirdly, the product of evapotranspiration could recycle continuously where it arises, and runoff through the river system would be compensated by import of primary vapor from the Atlantic.

Analysis of the stable isotopes of water, deuterium and oxygen-18, in rain and river waters[2,40], which makes it possible to distinguish ocean water from water produced by plants, shows the following picture.

As mentioned previously, Amazonian vapor is exported to the south, particularly in some months. This quantity, however, is relatively small in comparison to the vapor imported to the Amazon from the Atlantic Ocean[26].

Table 6. Summary of the results obtained by different researchers on the hydrological cycle of the Amazon region

Place and period	Lit. ref.	Methodology	Total (P) rain mm/year	Transpiration (T) mm/year	%	Evapotranspiration (ET) mm/year	%	Runoff (Q)%
Amazon Basin, 1972/75	28	Aerological	2328	–	–	1260 (r)	54.2	45.8
Region between Belém–Manaus in the same period	28	The same	2328	–	–	1000 (r)	43.0	57.0
The same place and period	28	Thorntwaite	2328	–	–	1330 (p)	57.1	42.9
Amazon Basin, 1931/60	52	Penman adapt.	2000	–	–	1168 (r)	58.4	41.6
Manaus region, the same	52	The same	2101	–	–	1569 (p)	73.4	26.6
Amazon Basin, 1931/60	30	Climatonomic	2379	–	–	1146 (r)	48.2	51.8
Ducke Reserve, 1965/73	37	Thorntwaite and Mather	2478	–	–	1508 (r) 1536 (p)	60.8 62.0	39.2 38.0
Amazon Basin, 10 years	13	Thorntwaite	2179	–	–	1320 (r) 1475 (p)	60.6 67.5	39.4 32.5
Amazon Basin, various periodes	3	Thorntwaite	2207	–	–	1306 (r) 1452 (p)	59.2 65.8	40.8 34.2
San Carlos, Venezuela, 1979/80	14	Direct water balance and class A pan	3664	1722	47	1905 (r)	52.0	48.0
Model Basin, 1980/81	20	Direct water balance (ET = P − Q)	2089	1014	48.5	1542 (r)	74.1	25.9
Ducke Reserve, 1976/77	20	The same	2075	1287	62.0	1675 (r)	80.7	19.3
Ducke Reserve, 1981/82	6	The same	2510	1172	46.7	1642 (r)	65.4	34.6

Observations: (r) = real evapotranspiration; (p) = potential evapotranspiration.
According to recent calculations the rate of groundwater formation is circa 20% in the Central Amazonian region; evapotranspiration, therefore, reduces to circa 50%.

Whether similar exportation occurs to the north remains to be decided by future study.

The portion of precipitation coming from transpiration shows a very high rate of recycling[40]. The period of the cycle is estimated at 5.5 days.

VII. Water as a means of transport

The water that cycles through biosphere and atmosphere is the means of transport of nutrients from the root system to the foliage of the trees.

As the soils consist essentially of clays and quartz sands, they are poor in exchangeable ions[1,46]. The primary input comes with the rain from the atmosphere, and the bulk of the nutrients is retained by the biomass[16,17]; it is internally cycled within the ecosystem by alternating assimilation and decomposition.

At this point we would like to draw attention to the function of biological activity in the canopy. Herbivores, fruit and nectar feeders and their predators reside primarily in the canopy. This includes monkeys, birds, sloths, small mammals and a rich community of arthropods. The food consumed is mineralized by digestion and excreted in the canopy.

From there it is washed off by rain and reaches the forest floor in the leaf drip and stemflow. The output of the terrestrial nutrient cycles (via litter decomposition and biological activity in the canopy) appears in the stream discharge[53]. Table 7 summarizes the data so far available on ion content in the water cycle as measured in the catchment areas of the Barro Branco (Reserva Ducke) and the Bacia Modelo[6,7].

As stemflow is only 0.3% of the water budget the quantity of nutrients returned to the soil in this fraction seems insignificant. However, ecologically it may be of importance because epiphytes (Bromeliaceae, Araceae, Orchidaceae etc), lianas and creepers may depend largely on this mineral source.

It is evident that even of the most adundant ions only a fraction appears in the stream discharge. The excessively scarce nutrients P, Ca and Mg are almost entirely tied up with the biosphere; little to nothing comes in by rain and virtually nothing is released into the streams. It comes as no surprise that phosphorus is considered the limiting factor of the Amazonian forest ecosystem.

Table 7. Nutrient ion content (kg/ha · y) in the water cycle as determined in the catchments of the Barro Branco (BB) stream (Ducke Reserve) and the Bacia Modelo (BM)

Ions	Rainfall		Leaf drip		Stemflow		Stream discharge	
	BB	BM	BB	BM	BB	BM	BB	BM
Cl^-	21.2	14.1	29.9	7.8	–	0.16	4.2	–
NH^+	6.0	–	7.4	5.6	–	0.03	0.2	–
PO_4^{3-}	0.104	0.231	0.266	0.415	–	0.012	0.008	–
Na^+	10.4	8.2	11.1	8.7	–	0.12	0.9	–
K^+	2.1	4.8	22.1	17.8	–	0.25	0.4	–
SO_4^{2-}	–	61.5	37.0	172.9	–	0.41	14.7	–
Ca^{2+}	–	–	1.0	7.2	–	0.06	–	–
Mg^{2+}	–	–	7.8	3.1	–	0.04	–	–

Observations: Measurements made using 3 gauges for rainfall in BB and 3 in BM, for leaf drip 20 (BB) and 30 (BM); for stemflow 36 trees. Bacia Modelo is located ~ 80 km from Manaus (Brazil–Venezuela road).

Stream discharge depends on the amount of and pattern of rainfall; heavy and abundant rains increase nutrient content in streams. The Barro Branco for instance, discharged 4.2 kg Cl^-/ha y in 1976/77 and 14.7 kg $(SO_4)^{-2}$, whereas the respective quantities increased to 9.0 kg and 32.0 kg in 1981/82. The relative deficiency in cations is responsible for the high acidity of the system.

The pH of the rain was 4.3 ± 0.6 in the Bacia Modelo (1980–1982). During the first period, 1976/77, the pH of the stream water showed a mean of 4.1, and for the second one, 1981/82, this value was 3.9.

VIII. Possible effects of deforestation

Among the many controversial publications on the Amazonian future (see Introduction) the book by Goodland and Irwin[11] with the dramatic title 'Amazon jungle: green hell to red desert?' gained perhaps the most public attention.

In one of its figures, reproduced here (fig. 10), the authors summarize the probable effects of deforestation. The data produced during the last two decades confirm most of these predictions.

Traditional subsistence agriculture poses no threat to the ecosystem as long as the population is sparse, as it still is in Central Amazonia. The clearings are small, and after the 2–4 years of production fast growing, secondary forest species close them again. Under the canopy of secondary forest the species of primary forest can germinate and grow again. The forest edge is near enough for effective recolonization.

However, large scale, long term deforestations of 100 km^2 or more, at a single go, as is the practice today, may lead to ecological disaster. For at least one to two years, and the in case of unsuccessful crops much longer, the top soil is exposed to the full impact of solar radiation, whereas a forest canopy absorbs $\simeq 50\%$ for assimilation and evapotranspiration, and reflects much of the rest to the atmosphere.

The mechanical process of forest clearing, especially by bulldozers, elevated temperatures in the soil, lack of litter leading to the destruction of the soil fauna, the absence of deep roots and irreversible, physico-chemical changes in soil structure[1], cause soil compaction. Hence, infiltration of rain is much reduced and superficial runoff increased. Such effects have been reported from Surinam[54] and the Peruvian Andes[43]. In 5-year-old pastures in the region of Manaus the infiltration rates are reduced to 10% of those measured in primary forest[45].

Increased runoff and the full mechanical impact of heavy rains lead to soil erosion. In view of the fact that 73% of precipitation falls in the form of heavy rains, and that the soils are partly sands and mostly clay with its physical instability in relation to hydrological conditions, this problem is particularly serious.

The INPA projects, still primarily engaged in studying the natural conditions, have no data yet on soil erosion. However, numerous investigations from tropical regions are confirming increased erosion as a consequence of deforestation[8,33,49]. Increased runoff into the streams and rivers means that part of the water, normally recycled by the forest, is lost.

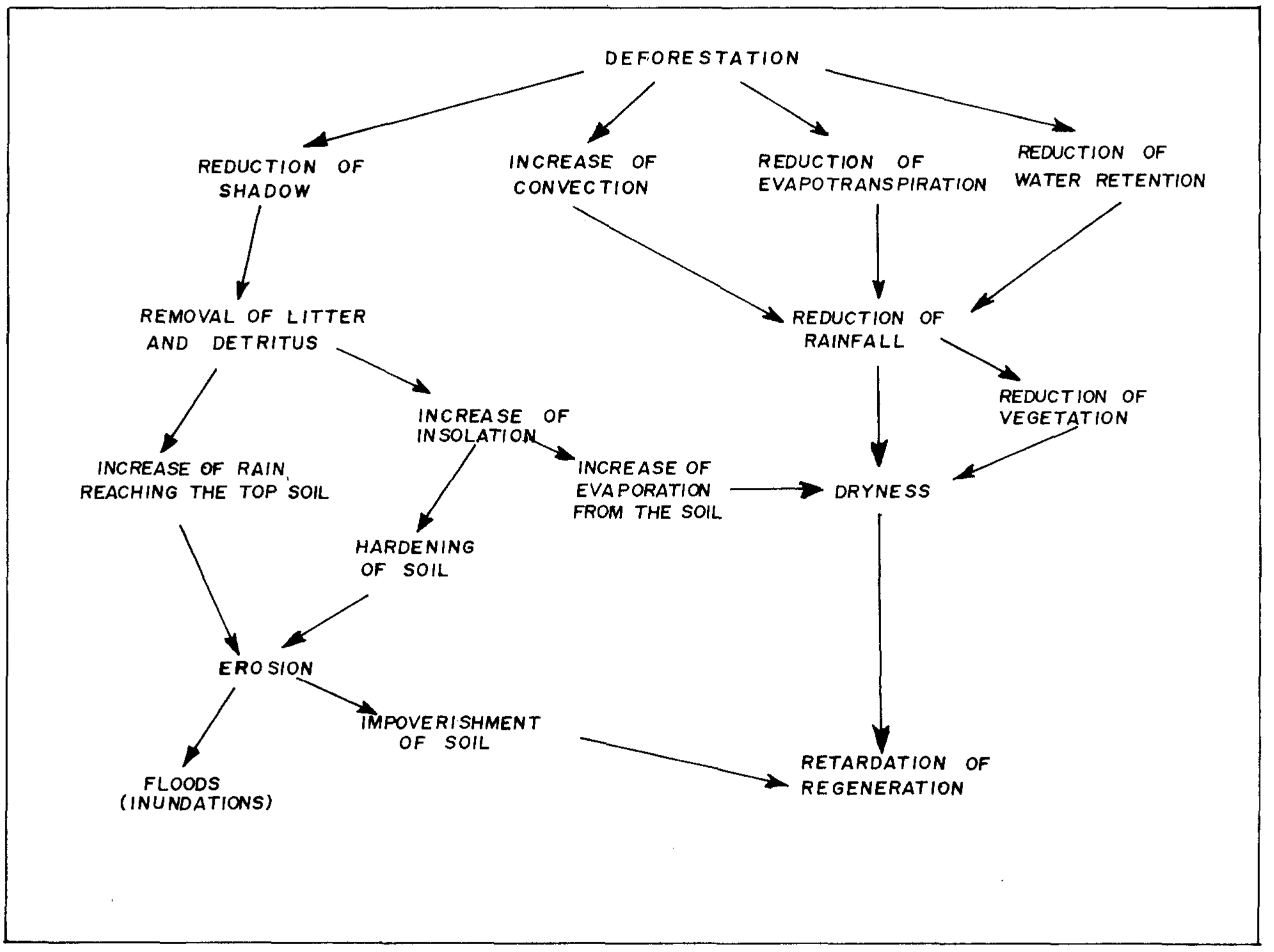

Figure 9. Ecological disturbance that may be caused by deforestation, after Goodland and Irwin[11].

Hence, evapotranspiration is expected to fall off in the long run, even if it were true, as some authors claim, that momentary (in case of a moist soil) potential rate of evapotranspiration of crops and pastures is of the same order of magnitude as that of an intact forest.

This reduced potential for retaining the water is particularly dangerous to the plateaux of the terra-firme[12], because the intact forest of these higher situated areas already operates under a water deficit during the drier months of the year.

Water is the means of transport for nutrient cycling, and deficiency of water implies deficiency of nutrients, especially in poor soils as are most of those in Amazonia. The role of forest litter and decomposition in nutrient cycling is the subject of a separate article in this review, and is therefore not considered here.

The biomass of the Amazonian forest consists, as does all plant matter, mostly of water. Under the canopy relative humidity approaches 100%[14,52], direct evaporation from the soil is about zero. Thus the Amazonian intact forest presents a $\sim$ 40 m high layer of water-saturated atmosphere that is protected against wind and heat convection by an ever-cooling canopy.

The Amazonian forest is therefore, first and foremost, a gigantic *water reservoir* that buffers diurnal and annual fluctuations of atmospheric parameters, (radiation, humidity, heat, precipitation). Whether the removal of the forest, i.e. of the reservoir, affects the input and output flows of rain from condensation of water vapor from the ocean; output through effluent rivers, remains to be established. Everything that depends on internal recycling within the reservoir is, of course, vitally affected. The annual fluctuations in forest and open vegetation on the Ilha de Marajó (fig. 6) demonstrate the long term homeostatic effect of the forest, while comparison of daily fluctuations of air and soil temperatures between high forest and open 'Campina' vegetation show the attenuating effect on short term fluctuations[36].

It is still early to conjecture about possible effects of deforestation outside the Amazon Basin. If exportation of Amazonian water vapor is important for the southern, and naturally drier regions, they are likely to suffer from increased dryness. There is little doubt that the Amazon Basin will be more intensely colonized by Man in the future. No country can be expected to leave half of its land to the wild beasts, however desirable this may seem to outside populations which have essentially destroyed all of their own natural ecosystems. It is, however, in the interest of the present and future populations of the Amazon Basin to slow down deforestation before irreversible harm is done, and to invest a major effort in the search for sound methods of land use which are specially adapted to the precarious conditions of soil and climate in this region.

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