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THE WATER CYCLE IN TROPICAL FORESTS, WITH SPECIAL REFERENCE TO THE AMAZON

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SUMMARY

Tropical ecosystems were comparatively little disturbed during the colonization period, which started in the XVI Century. The difficulties encountered in establishing economically feasible production systems hampered the setting up of agricultural activities in the humid tropics. This difficulty still exists and even with present agronomic technology, many of the large scale attempts to use the humid tropics have failed. Therefore, as far as flora and soil quality are concerned, the humid tropic regions have only suffered major changes during the last 30 years, and in the Amazon region pressure has been exerted only during the last 10 years.

Until recently very little research work had been carried out to determine the relationship between plant cover in the area and the regional or global characteristics of the atmosphere. Our work has been developed in the Amazon region and we have tried to establish the relationship between the present climate equilibrium and the dense forest cover which extends over an area of more than 5 million km^2. The research was carried out in successive stages, involving analysis of surface meteorological data, radiosonde data, satellite photographs, and analysis of chemical and isotope composition of rain water.

The general conclusion obtained through the different approaches was that the present dynamic equilibrium of precipitation and water regime

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depends on plant cover. The possible changes are analysed as a function of the available information.

Introduction

The depletion of tropical rain forest is a comparatively recent phenomenon, with deforestation taking place at an ever increasing rate during the last 30 years. The tropical forests were comparatively little disturbed during the early colonization period, starting in the 16th Century. There were many reasons for this: the forest was a natural barrier and transport was difficult, hostile indigenous peoples made isolated settlements vulnerable, disease was (and still is) a major problem, and, maybe above all, it was quite difficult to establish large scale agricultural systems.

For example, all these factors have operated in Amazon. Even during the rubber boom of the late 19th Century colonization was primarily confined to locations on the riverbank which could be reached by boat. It was calculated that completion in 1912 of the Madeira-Mamoré railway line of 364 km cost one life for every sleeper laid (de Oliveira, 1983). We now know much more about tropical diseases, but the problems are far from being solved (da Costa Linhares, 1983). Failure in exploitation may be due to unexpected reasons. The well-funded rubber plantation of the Ford Motor Co. (Fordlândia) established near Santarem in the 30's failed by 1944 primarily because of fungus disease and an insect parasite. This was not a problem with the isolated trees of natural rubber in the jungle, but under plantation conditions the trees were close enough together for the infection to pass from one to another. At that time no effective pesticide treatment was available.

The frequently poor soils have led to much difficulty in establishing large scale cropping or pasture systems. The forest is virtually a closed system as regards nutrients, and except for nitrogen and phosphorus which are primarily in the soil, most of the nutrients are in the trees and litter (Klinge, 1976). When the forest is cleared by burning, the nutrients are in the ash and are readily lost by rain; at most they provide nutrients for two crops. This is the basis of the shifting cultivation of the indigenous people: when the land is exhausted they move to a new area. Permanent agriculture requires soil management to prevent erosion and fertilization to maintain fertility, and this has been lacking. This information is slowly being acquired (Sanchez *et al.*, 1982), but even in the last few years the simple failure to apply phosphate fertilizer to pastures established on cleared forest at Paragominas near Belem has resulted in over 500,000 hectares of land being degraded, with severe erosion (Serrão *et al.*, 1979).

Despite these prohlems better knowledge of how to develop tropical forest areas, plus population pressure and financial incentives have resulted in the loss of half of tbe World's tropical forests, during the last 30 years. It is estimated that at the current rate over two-thirds of the remaining rain forest will have been lost by the year 2000 (Salati and Vose, 1983a). Estimates are that, as a minimum, 6 million hectares of primary forest are converted to secondary forest annually through selective logging, and a further 3 million ha converted to pasture and cropping. In Amazon alone the latest figures (Anon, 1982) suggest that a minimum of 2.3 million hectares of forest are being cleared annually.

Such extensive deforestation may possibly have profound effects on atmospheric chemistry, rainfall, and other climatic factors. Therefore, almost implicit in any consideration of the water cycle in tropical forests is the question: what effect does deforestation have? That is the theme of this presentation.

Tropical Forests and Hydrology

On the whole hydrologists have been inclined to discount the possibility of land use changes affecting rainfall (Pereira, 1973). Moreover there has in the past been a tendency to minimize the role of recycling (UNESCO, 1971). Indeed, Linsley (1951) suggested that the concept of evaporation from the land is not important for continental precipitation, and therefore deforestation and improved drainage will have little effect on regional precipitation regimes. However, this view is changing and a recent report (WMO, 1983) notes, "it is possible that changes in land-use/land-cover may produce changes in the meteorology and certainly produce significant changes in the hydrology of the areas affected".

Why in the past has the potential rôle of precipitation recycling by tropical forest been minimized? There seem to be six or seven reasons for this: it is in the last 20 years that the rate of tropical deforestation has increased so greatly, previously the areas converted were small in relation to the whole; changes in land use have often taken place before definitive hydrological or local meteorological studies, so there is no good "before" and "after" data; there has been a tendency to regard regional and sub-regional vegetation habitats as being defined mainly by soil type and temperature rather than rainfall regime; there has been an inclination to consider that evaporation is about the same for different vegetation types and is only reduced when rainfall itself is the limiting factor; the increased precipitation run-off resulting from deforestation, with consequent loss of water from the system, has not been adequately taken into account; in many areas of the world the probability of a major advective oceanic water contribution to precipitation e.g. in the tropical forest areas of S.E. Asia and Oceania, has masked the contribution from recycling.

Probably we have been fortunate in studying the water relations of tropical forests in the Amazon Basin because we bave a clearly defined region, located on the Equator with a uni-directional source of oceanic water. Thus the horseshoe shaped Basin is characterized by a large plain bounded on the West by the Andes which are approximately 4000 m high, while in the North the Basin is limited by the Guiana Plateau having altitudes as high as 1000 m. To the South the Basin is bounded by the Central Plateau of Brazil with an altitude of about 700 m. The prevailing Trade winds blow almost continuously from the East and penetrate the whole region, hringing in oceanic water from the Atlantic. The result is a hot and humid climate which, over millennia, has led to the development of the tropical forest of central Amazon. Considered theoretically, if the forest were to be totally removed, there seems little doubt that, *if left undisturbed and similar global conditions existed*, a forest would again develop.

The timescale for this renewal is unknown, although palaeoclimatic evidence suggests it would be at least a thousand years, as can be seen from Table 1, due to Prance (1978) who used palynology data from Van der Hammen (1972, 1974) and comparable Mexican chronology. More recent pollen studies combined with 14-carbon dating suggest that there has been little grassland in the Manaus area since 4,000 B.P. (Absy, 1979; Irion, 1982). Charcoal has been ^{14}C dated to 3,000-6,000 B.P., implying a drier climate that made forest fires possible (Soubies, 1980). In reality of course the land now being cleared in Amazon will not remain undisturbed, as the present rapid changes in land use now taking place i.e. roads, pasture, crops, mining, industry, etc. will result in semi-permanent modification.

Cochrane and Jones (1981) have argued convincingly that the savannas of tropical South America occupy a well defined habitat delimited hy the climatic potential for growth. This has been defined primarily

TABLE 1 - *Climate and vegetation change in Amazon* (due to Prance, 1978).

Date before present (Millennia)	Climate	Duration (years)	Vegetation
Last glacial period			
12,000	wet and cold	1,000	forest returning
11,000	dry and hot	1,000	savanna
10, - 9,000	wet and cold	2,000	forest
9, - 2,000	dry and hot	7,000	savanna with large forest refuges
2,000	slightly wet and slightly cold	1,000	forest

by the wet season potential evapotranspiration regime, which was found to be about 900 mm for savanna having a 6 months wet season. Tropical forest can be similarly characterized, and it is interesting to compare the savanna figure with the Amazon forest, where evapotranspiration is of the order of 1200-1600 mm yr^{-1}. Even more significant is the comparison of precipitation and evapotranspiration for oceans, continents and Amazon shown in Table 2. It is clear that the high Amazon evapotranspiration rate is much more characteristic of oceans than it is of average continental evapotranspiration.

TABLE 2 - *Comparison of precipitation and evapotranspiration in Amazon with averages for oceans and continents.*

	Precipitation mm yr^{-1}	Evapotranspiration mm yr^{-1}
Amazon	2300	1200 - 1600
Continents	710	470
Oceans	1100	1200

The close connection between the forest and precipitations is clearly indicated by the preferential development of local cloud over the forested areas of Amazon and, viewed from the air, great "pillars" of cumulus sometimes appear to arise from the very top of the forest. For example Friedman (1977) noted that the western half of Marajó Island, which is heavily forested, received daily rain throughout the year. While thunderstorms built up over the forested half, none appeared over the treeless savanna eastern half.

As the Penman equation (Penman, 1963; De Bruin, 1983) for estimating evapotranspiration can be applied to different vegetation types including, with some modification, forest, there has been a tendency to believe that combined evaporation and evapotranspiration should recycle water to the atmosphere to the same extent whatever the type of vegetation e.g. whether forest, pasture or annual crops. Data from the Zaire Basin (Penman, 1963; quoted hy Edwards and Blackie, 1981) have been supportive of this view, but what is overlooked is that a large part of the Zaire Basin is swampland, and that the conclusions are based on simple measurements of relatively undisturbed vegetation. Moreover, considerations based simply on evapotranspiration do not take into account the fact that deforestation tends to increase surface run-off, with reduced water recharge of the soil systems. Thus although there may be still high evapotranspiration following deforestation, it is likely to be drawing from a decreased soil water store.

Recent thinking has suggested that water consumption from bare soils and partial vegetation cover is between 400 and 500 mm yr^{-1} whereas the corresponding figure for mature forests is 700-900 mm yr^{-1} (Baumgartner, 1979). Similarly Molion and Bettancurt (1981) have demonstrated that evaporation differences among cover types, assuming water is not limiting, can he quantitatively explained purely in terms of energy considerations, and that forests evaporate more water than any other cover type, as much as twice that from bare soil. Practical reasons support this: tree roots exploit a large volume of soil to greater depths than most annual crops or replacement vegetation and water recharge of forest soils is good.

Simple logic dictates that if forest is cleared then the resulting decrease in evapotranspiration must lead to increased run-off, if precipitation remains the same in the short term. The problem can also be approached from the opposite point of view: what effect has deforestation on run-off? It should be noted that the forest canopy protects the forest floor from the direct impact of rain, while surface litter and organic matter helps to ensure good water absorption. The vegetation maintains a good soil structure and thereby maintains percolation and good water recharge of the system.

Reduced infiltration rates on newly cleared tropical forest soils is found to he normal (Sanchez, 1976), and especially in Surinam (Van der Weert, 1974) and in Peruvian Amazon (Seubert, 1975) has been especially associated with compaction effects from bulldozer clearance. Schubart (1977) reported for cleared primary forest near Manaus that infiltration rates of 5 year old pasture were less than a tenth of the rates for forest. Charreau (1972) found in West Africa that run-off was 20 or more times greater from cultivated and bare soils than from forest.

Deforestation does not always result in increased run-off: Bonell *et al.* (1983) found in tropical rainforest of Queenland, Australia, that the prevailing rainfall intensities (4239 mm yr^{-1}) frequently exceed the saturated hydraulic conductivity of the profile. There is therefore rapid saturation of the top layer and the generation of surface flow; thus no change in run-off hydrology occurred following deforestation although clearing increased soil erosion rates tenfold. In general, deforestation seems initially to increase peak run-off of river flows, which later stabilize at lower levels. 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 catchment low flows were reduced to one-quarter (Daniel and Kulasingam, 1974). In Guatemala the once major Montagua River is more than 50 per cent reduced in volume, following the loss of 65% of natural forests during the last years (Troughton, 1980).

Fate of Precipitation Falling on the Forest

Interception, Throughfall and Evapotranspiration

The impact of forest on the hydrology and climatology of a region must in effect be the sum of events taking place on individual forested areas, such as watersheds and hasins. The interception of precipitation and evapotranspiration by the forest are major events which can be determined over a defined area. In Brazil, measurements of interception in sub-tropical forest were carried out by Freise (1934, 1936) almost fifty years ago. He found that 34% of precipitation became throughfall, 28%

represented stem flow, 20% was evaporated from the crown of the trees with 18% assigned to general evaporation and losses in the bark.

More recent work has not confirmed the large proportion of stem flow. Work by Franken *et al.* (1982), carried out in typical Amazon high forest near Manaus, used a system of rain gauges in cleared areas and in the forest canopy, with an extensive series of stem flow collectors. They found that 77.7% of average precipitation reached the soil surface as throughfall, 22% of the rain was intercepted by the canopy, while stem flow only represented 0.3% of the total.

Clearly, local conditions, such as tree species, the number of trees per unit area and the average intensity of the precipitation will affect the proportions. Thus in the Amazon forest in the region of San Carlos, Venezuela, Jordan and Heuveldop (1981) found 87% throughfall and 8% stem flow, while only 5% of precipitation was intercepted.

In Malaysian tropical forest Sim (1972) found that interception varied between 25 and 80% as a function of precipitation class. Near Manaus, interception of rainfall, Table 3, was as great as 84.6% for the rainfall class of > 5 mm, with a throughfall of only 15.4%, while for the rainfall class 60-70 mm interception was reduced to 25.5% and throughfall increased to 74.1%. Stem flow was negligible regardless of rainfall class (Franken *et al.*, 1982).

A further estimate of evapotranspiration was made (Leopoldo *et al.*, 1982b) for high forest on a model basin of 23.5 km^2, 60 km north of Manaus, which is drained by a large stream. This area has an average rainfall of 2000 mm. Measurements were made of precipitation, inter-

TABLE 3 - *Forest throughfall related to rainfall intensity* (Franken *et al.*, 1982).

Rain Distribution	< 5.00 mm	5-10 mm	10-20 mm	60-70 mm
		per cent		
Interception	84.6	41.2	28.7	25.5
Stem flow	0.0	0.0	0.2	0.4
Throughfall	15.4	58.8	71.0	74.1

ception and drainage, making it possible to calculate evapotranspiration. The combined results of the two studies (Franken *et al.*, 1982 and Leopoldo *et al.*, 1982b) showed that on average 25.6% and 18.7% of rain was intercepted by the forest and evaporated to the atmosphere, while 48.5% and 62.0% was transpired by the forest, while run-off accounted for 25.9% and 19.3% respectively at each location. This means that evaporation and transpiration combined represented as much as 74.1% and 80.7% at the two sites (Figure 1).

Water transit time in forest soil

It has been found that certain heavy rainstorms have enhanced concentration of the heavy isotope ^{18}O. The difference in ^{18}O concentration between the storm rain and the existing soil water has made it possible to trace the passage of the naturally labelled rain down the soil profile as in Tahle 4 (Leopoldo *et al.*, 1982a). It can be seen that although a rainstorm very quickly penetrates a depth of 15-25 cm and reaches 50 cm depth in 2 weeks, it can take almost two months to be detectable at 120 cm depth.

Further studies followed the annual variation in ^{18}O and Deuterium content of precipitation and of stream water. It was found that the isotopic composition of the rainwater varied with season of the year, but this was not reflected by changes in the drainage water, suggesting a mixing of waters and a high soil water storage.

TABLE 4 - *Transit time of rainwater in Amazon forest soil determined by* $\delta\,^{18}O$ (Leopoldo *et al.*, 1982a).

Depth	*Time*
15-25 cm	1 week
50 cm	2 weeks
80 cm	3-4 weeks
120 cm	5-8 weeks

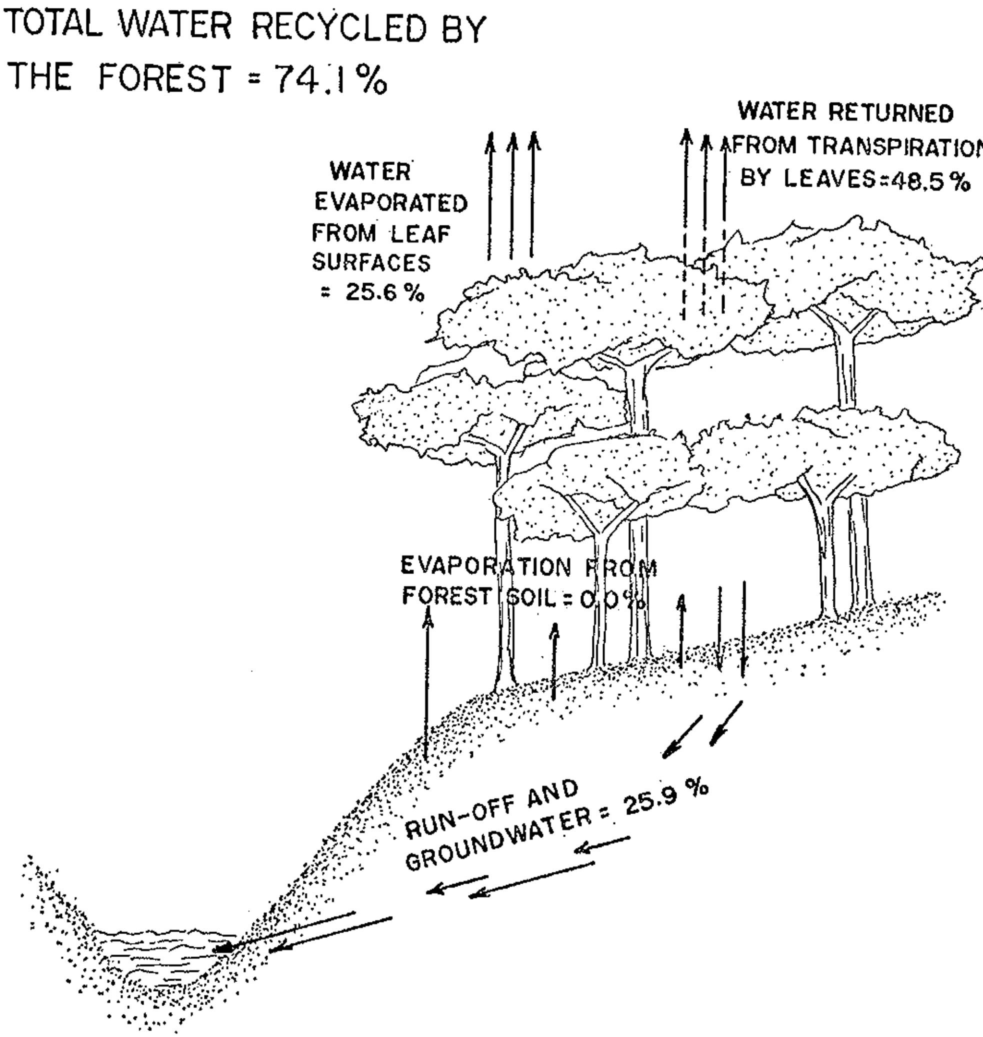

FIG. 1. Fate of precipitation falling on Amazon high forest.

Gonçalves (1979) studied the residence time of superficial waters in some hydrographic basins in Amazon and found values varying from 1.1-2.3 months. Salati and Ribeiro (1979) noted that deforestation in the Amazon Basin is likely to reduce the water residence time.

Water Balance and Recycling of Precipitation

The estimates of evapotranspiration of high forest given in the previous section, clearly relate to a local situation. Average evapotranspiration, and related recycling of precipitation must clearly he less, because not all of the Basin is covered with forest. Water balance and recycling estimates are possible because of the measurements of the Amazon River flow made by Oltmann (1967). Water balance can be estimated by meteorological data or radiosonde data and recycling confirmed by stable isotope technique.

Evidence for water recycling using climatological methods

Molion (1975) employed climatological data (average charts of wind and specific humidity seasonal values) and the method of Penman (1963) to estimate that about 52% of the rain falling on the region was lost through the river. Similarly Villa Nova *et al.* (1976) applied Penman's method adapted to forested regions by Shiau and Davar (1973) and calculated that evaporation represented 54%, and 46% of rainfall was lost to the river.

Allowing for the scale of the system and the inherent inaccuracies these estimates are very close.

Evidence for precipitation recycling using aerological methods

Marques *et al.* (1977) obtained data for water vapour fluxes and computed precipitable water from the analysis of 658 daily meteorological upper air observations by radiosonde at stations in Manaus and Belem. The study showed that the Atlantic Ocean water vapour contributed 52% to regional precipitation, and that the water vapour was predominantly supplied to the region by the flux in the east-west direction. It was noted that a significant role is played by local evapotranspiration in the generation of rain in the area. Evapotranspiration apparently contributed to 48% of the rains in the region studied.

Taking the studies together it can be concluded that the Amazon Basin receives 11.87×10^{12} m^3/year of rain water, losing 6.43×10^{12} m^3 through evapotranspiration and 5.45×10^{12} m^3/yr through river discharge (Fig. 2). Marques *et al.* (1980) observed that the amount of water vapour coming from the ocean is of the same magnitude as that lost through the evapotranspiration. It should be noted that the calculation of water vapour from the ocean is by methods and data quite independent of the calculation of evapotranspiration.

Isotopic estimation of water recycling

Another independent method has been used to prove and estimate the recycling of water vapour in Amazon, using ^{18}O and D (deuterium) concentrations in rain and river waters (Salati *et al.*, 1979). The isotopic method is simple in principle and gives a deeper insight into the hydrological cycle, such as an estimate of the water vapour that enters and leaves the region.

Water has various molecular species depending on the hydrogen and oxygen isotopes of which it is composed. The stable hydrogen isotopes are ^1H and ^2H or D. The stable oxygen isotopes are ^{16}O, ^{17}O and ^{18}O. Different species of water molecules are formed by the combination of these various isotopes, e.g. $HH^{16}O$, $HH^{18}O$, $HH^{17}O$, $HD^{16}O$, etc. Of these molecules the most important, due to their concentration and interest for our application, are $HH^{16}O$ and $HH^{18}O$.

In the process of evaporation of water in the ocean, molecules of the type $HH^{16}O$, which have a molecular mass equal to 18, are evaporated before molecules of the type $HH^{18}O$ which have a molecular mass of 20. During evaporation there is, therefore, an isotopic fractionation and the vapour from sea water has an ^{18}O concentration about 8% less than the ocean concentration. As this water vapour enters the continent it will condense and probably precipitate to become soil and river water. Since the heavier molecules condense first, the process of cloud formation and precipitation leads to isotopic depletion of residual water vapour. This should mean that, with a prevailing easterly wind, the water vapour of the westerly regions should have a lower concentration of ^{18}O.

Systematic measurements of the isotopic composition of the Amazon region rain were made, and it was noted that the decrease in ^{18}O concentra-

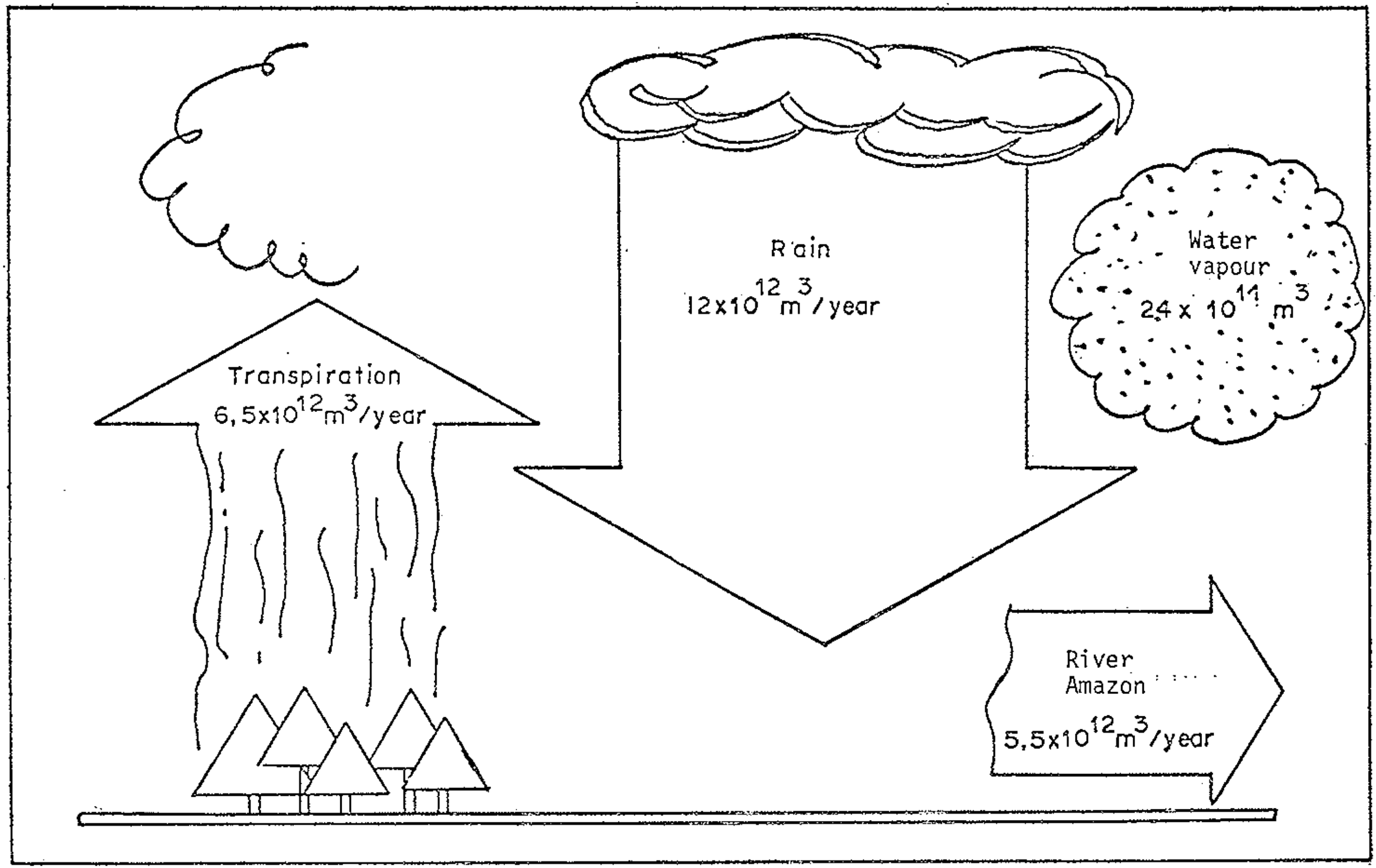

FIG. 2. Gross water balance in the Amazon Basin (Marques *et al.*, 1979).

tion was less than that expected in a process of continuous removal of water vapour through precipitation. This situation might be explained if we suppose that the water vapour produced by evapotranspiration mixes with the oceanic vapour and that rain in a certain place is formed by a mixture of these two vapours.

Measurements of ^{18}O and D in rain and river waters have indeed made it possible to confirm (Dall'Olio *et al.*, 1979; Salati *et al.*, 1979) the importance of re-evaporated water for the water balance throughout the Basin, and in particular to establish a model indicating the relationship with the new oceanic water. There is a predominant zonal flow from east to west (Newell *et al.*, 1972) and vapour influx from the Atlantic Ocean was estimated from the wind and humidity measurements by radiosonde at Belem. The central east to west region of the Basin between 0° and 5° of the latitude was considered to be subdivided into eight 3° segments between Belem (48° 30′) and just west of Benjamin Constant (72° 30′).

Overall the small inland gradient of the isotopic composition of the precipitation confirmed the importance of the re-evaporated moisture in the water balance of the area. A model was then developed as in Figure 3, which suggests that in any one segment the rainfall comprises about half derived from evapotranspiration within the segment area, while the other half comes from water vapour derived from the neighbouring eastern segment, conveyed by prevailing winds.

Interaction of Local and Continental Factors in Amazon

As we have noted, there is good agreement between evidence for water recycling in the Amazon obtained with different methods, such as the more conventional climatological ones and the more recent aerial and isotopic methods. However, in an overall consideration of precipitation patterns in Amazon it is necessary to distinguish between the locally derived cumulus clouds, mainly involved in the recycling process, and which are initiated by latent and sensible heat, and the high tropospheric clouds of the South American Continent. There is still little information as to the manner and extent to which local recycling interacts and is influenced by continental factors.

In the Amazon Basin there are two different rainfall regimes — in the central part and a portion of the western area of the Basin there is a definite dry period, but in the eastern and western end of the Basin there

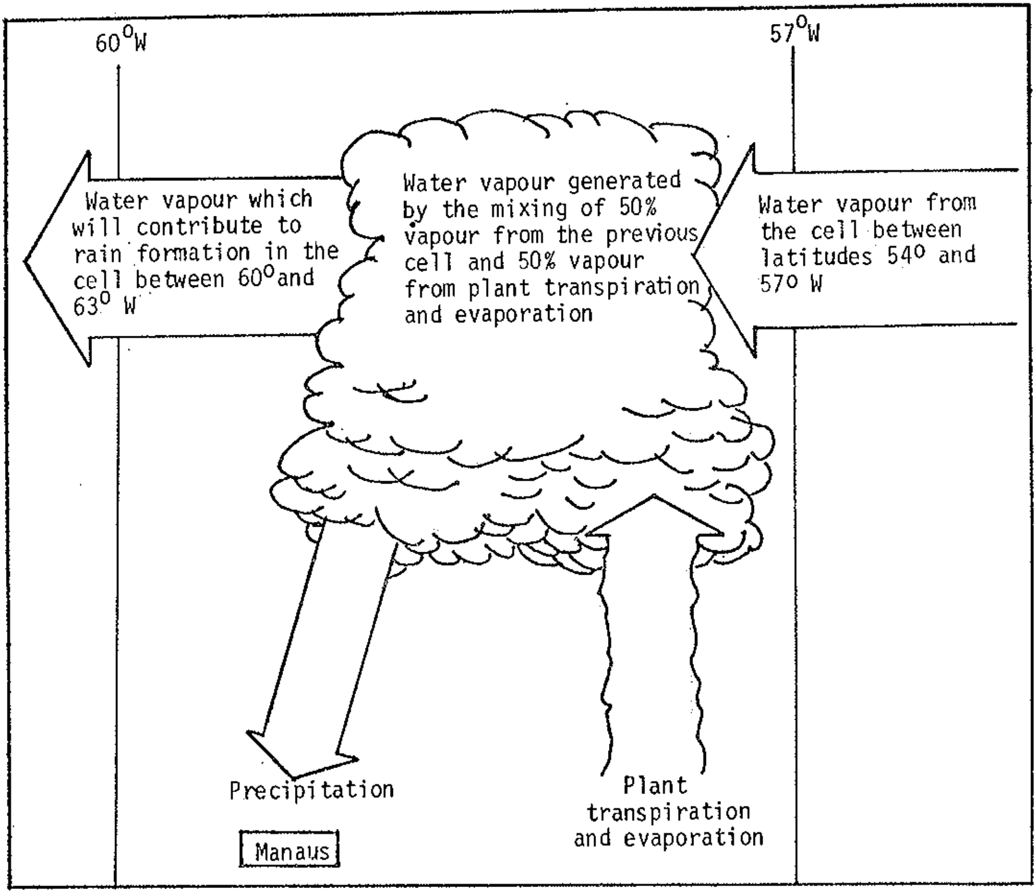

FIG. 3. General scheme to explain rain formation in Amazon from two sources of vapour: the Atlantic Ocean and the forest. The region was divided into 3° longitude strips. The above scheme indicates the city of Manaus (Dall'Olio *et al.*, 1979 and Salati *et al.*, 1979).

are frequent rains the entire year. The Amazon climate is characterized by mainly easterly winds and the main influx of advective atmosphere water into the Basin comes from the Northern Hemisphere Trade winds.

Classically, it has been considered that the different rainfall regimes are determined by interception of the Intertropical Convergence Zone (ITCZ) and the Equatorial Atlantic air mass in the case of the eastern region and the presence of the Equatorial Continental air mass in the western-most regions. Satellite imagery from LANDSAT has suggested (Salati *et al.*, 1979) some revision of this classical description. They did not find indications of north-south movement of water vapour within the Basin as would be expected from the entrance of an air mass from the North Atlantic.

Kousky and Molion (1983) have more recently described the tropospheric circulation pattern and its relation to rainfall in the Amazon Basin. They noted that in summer the general pattern of precipitation is closely linked to the position of an upper tropospheric high pressure system whose centre generally forms over Bolivia and which dominates the circulation over South America. This system weakens and tends to move northwards during fall and winter, corresponding to the dry season in the southern regions of the Basin. These studies suggest that variability in the rainfall pattern may be due partially to persistent convergence zones, originating from or associated with Southern Hemisphere frontal systems. Additionally, there appear to be lines of instability associated with maritime winds. On occasion these lines propagate inland and can apparently remain active for up to 48 hours during which time they cross the entire Basin, as far as the Andes.

These large scale circulation effects are not inconsistent with the data of Salati *et al.* (1979) who noted a distinct seasonal and regional pattern of stable isotope composition, thus indicating the Basin to be inhomogenous from the hydrometeorological point of view. For example, during the months of July-September there was a complete absence of an inland $\delta\,^{18}O$ isotope gradient. It was concluded that there are additional sources of advected moisture in the interior of the Basin, and that the assumption of negligible latitudinal air exchange breaks down in the western part of the Basin, which is an area of convergent flow.

Although the isotope data confirmed that evapotranspiration becomes the dominant factor during the Southern Hemisphere winter months, it was observed that while large amounts of water are apparently recycled in the central and eastern part of the Basin, in the western and southern margins the role of evaporated water is less important.

Unusually low $\delta\,^{18}O$ values are sometimes found throughout the Basin during April and May, and occasionally during the late summer months of December-March; and these are not due to any large inland isotope gradient. It is concluded that the low isotopic values are imposed on the Basin from the outside. During this period the ITCZ moves southwards into the latitude of the Amazon Basin and there is a marked connection between the position of the ITCZ and the isotope data, implying that the vertical mixing in the Convergence Zone and the resultant cloudiness affects both the isotopic composition of the rain patterns. Satellite pictures showed seasonal shift in the wind pattern such that the latitudinal component of air motion is clearly mirrored by the isotope data (Salati *et al.*, 1979).

Thus, although on average about half the water vapour in the Amazon Basin is recycled, external factors, apart from the regular water vapour influx from the North Atlantic, exert from time to time a major influence on the system. The nature of these effects and further knowledge of vapour flows into and out of the Basin requires further monitoring of precipitation patterns and isotopic analysis over a wider area, coupled with radiosounding studies (Salati *et al.*, 1983a).

The Forest and Atmospheric Chemistry

Away from cities the natural background level of chemical species in Amazon Basin atmosphere is extremely low. Thus, Artaxo Netto *et al.* (1982a,b) used proton induced X-ray fluorescence analysis (PIXE) to determine that the total concentration of the natural Amazon aerosol was under 10 $\mu g/m^3$, one of the lowest natural backgrounds ever recorded. This measurement was taken about 60 km north of the busy city of Manaus, confirming incidentally the prevailing east-west direction of the wind.

C, N and O comprise the major portion of the substrate particles, amounting to 80% of the total mass of natural aerosols and 99% of aerosols from brush-fire areas. As would be expected, deforestation by burning adds substantially to the aerosol nutrient content, as shown in Table 5. From this and the work of Lawson and Winchester (1979) there seems to be general agreement that large particulate matter of natural aerosols, such as Al, Si, Ca and Fe come from the soil, while fine particulates like S and K come from vegetation.

As already mentioned, the mature Amazon high forest is almost a closed system as regards nutrients. Few nutrients are lost, and these are balanced by inputs of nutrients in precipitation, although the concentration is low. Thus preliminary data for nitrogen have been calculated for the model basin near Manaus (Salati *et al.*, 1982) and it was found that for the months of May and June 1980, total mineral N input was 0.022 and 0.020 kg N/ha^{-1} respectively. This is clearly a very low input, even when expressed on an annual basis. Greater total-N figures were calculated from

TABLE 5 - *Concentration* ($ng.m^3$) *of elements in Amazon aerosols* (derived from Artaxo Netto *et al.*, 1982a).

Element	Natural forest aerosol 60 km north of Manaus	Typical aerosol from forest burning area, valley of Rio Madeira
Al	43.59	6264
Si	74.41	31812
P	13.30	20172
S	374.10	18254
Cl	72.99	9170
K	189.90	42378
Ca	24.81	37345
Ti	7.04	1234
V	9.36	2066
Cr	3.72	143
Mn	0.82	2405
Fe	37.96	2816
Ni	1.95	0
Cu	0.23	434
Zn	9.31	318
Br	1.66	727
Pb	5.01	1482

regional analyses of rain water, indicating a basin-wide input of about 4-6 kg N ha^{-1} yr^{-1}.

Based on the data of Stallard and Edmond (1981) it can be calculated that "average" Amazon rainwater contains (μ moles l^{-1}): 12.4 Na, 1.0 K, 1.2 Mg, 1.1 Ca, 13.7 Cl, 5.1 SO_4, 2.1 NO_3, 0.5 NH_4 and 0.0 Si. Of course there is some variability depending on location, etc. This is well seen in the case of Cl^-, the concentration of which declines from east to west and is negligible in upper Amazon precipitation; tending to confirm the insignificance of Pacific Ocean water for Amazon precipitation.

Apart from the release of inorganic chemical species by forest burning, the major effect of deforestation is to add substantial amounts of CO_2 to the atmosphere (Bolin, 1977; Bolin *et al.*, 1979; Woodwell *et al.*, 1978).

As is now well known, the significance of increased atmospheric CO_2 concentration is that CO_2 is a key absorber of thermal infrared radiation in the atmosphere, and a large increase in global CO_2 levels could result in global temperature rise (Woodwell, 1978; Niehaus, 1979).

Estimates of standing biomass in the Amazon high forest are 500-1000 tons ha^{-1} and it is the largest remaining tropical forest. One calculation has estimated (Troughton, 1980) that if half its carbon was released over the next 20 years, and half of that amount remained in the atmosphere, then it would increase the CO_2 concentration of global atmosphere by about 5%. The Amazon River carries much particulate and dissolved organic carbon to the ocean, much of which must ultimately become CO_2 Similarly, major forest debris such as floating logs, have been calculated to contribute approximately 1.6×10^6 t C yr^{-1} to the biosphere (Kempe, 1982; Richey, 1982).

The soil organic matter of cleared tropical forest contributes substantially to atmosphere CO_2 About 25% of organic carbon is lost from forest soils within 12 months of clearance (Miller *et al.*, 1982). When it is considered that a typical forest soil contains over 100 ha^{-1} of organic matter in the first 30 cm and about the same amount from the 30-100 cm horizon (Klinge, 1976) then it is clear that the potential production of CO_2 is very high. Ewell *et al.* (1981) studied slash and burn technique at a Cost Rican wet forest site. They found that after burning, the forest soil evolved CO_2 at such a rate that after 154 days decomposition and respiration as much C would be released into the atmosphere as was released by the burn.

Globally, the net carbon loss from tropical forests into the atmosphere from tropical deforestation and changes to secondary forest, pasture and crops, has been estimated (Seiler and Crutzen, 1980; Dickinson, 1981) to be about 1.0×10^{12} kg carbon, or equivalent to about 17% of that due to fossil fuel burning. This amount tends to support the view that the current increase in atmospheric CO_2 is primarily due to increased fossil fuel combustion (Niehaus, 1979; Broecker *et al.*, 1979). Nevertheless, there is sufficient uncertainty in the basic data, e.g. the rate of deforestation and the amount of biomass, to permit wide variation in the final estimates. Thus, other estimates have suggested that the release of carbon due to tropical deforestation is 3×10^{12} kg carbon or even more, with overall releases from biota estimated to approach 6×10^{12} kg carbon (Woodwell, 1978; Woodwell *et al.*, 1978). This latter amount is more or less equivalent to that released by fossil fuels.

Potential Effect of Deforestation on the Regional Water Cycle

The solar energy which falls on the central Amazon region i.e. near Manaus is on average 425 cal cm^{-1} day^{-1}, which is used principally for evaporation of water and the evapotranspiration of plants (Villa Nova *et al.*, 1976). It is estimated that 50-60% of the solar energy is used in this way.

In the case of deforestation on a large scale the energy balance will be altered. A large part of the energy which today is used by plants in the process of transpiration will be used for heating the soil and air. The water balance is inevitably related to the energy balance, as indicated in Table 6. It is clear that the Bowen ratio of sensible to latent heat will be modified by removal of forest, and this represents change in the exchange of energy between surface and atmosphere. Fraenzle (1979) has noted that quite a large change in albedo does not yield a significant change in production of sensible and latent heat. The Bowen ratio can be greatly altered by deforestation but sensible heat remains essentially the same in the short term, so what is changed is principally evapotranspiration.

Deforestation will affect the water cycle directly with a tendency towards greater surface run-off, as the replacement vegetation or bare soil

Table 6 - *Forest Energy and Hydrological Cycles are Linked.*

$$\text{Albedo} = \frac{\text{Reflected Solar Energy}}{\text{Incident Solar Energy}}$$

= 0.13 Tropical Forest
0.16 Savannah
(0.1 - 0.5, Soil)

$$\text{Bowen* Ratio} = \frac{\text{Sensible Heat (H)}}{\text{Latent Heat (Evaporation)}}$$

= 0.25 (Forest)
0.50 (Bare Soil)
2.00 (Extreme Suggestion for Cleared Amazon)

* Changes primarily due to E.

will retain much less water. Even with techniques such as contour ploughing and terracing, the water loss from surface run-off will be greater, and the soil less permeable than the forest soil with its mass of roots. Thus there will be an increase in the amount of water drained off by streams and rivers, especially during heavier rains, and a corresponding decrease in the amount of water available for evaporation and transpiration.

With less water available for evapotranspiration there will be a decrease in relative air-humidity, which will alter the energy balance. The incident solar energy instead of being used for water evaporation will be used for heating the air. This phenomenon was noted by Ribeiro and Santos (1975) in an area of "campina" near Manaus, where air temperatures were found to be much higher than in the forest. Similarly Cunningham (1963) recorded that forest clearance in Ghana resulted in maximum soil temperature at 7.5 cm depth increasing from 27 to 38 °C. The effects of deforestation on air temperature can therefore be noted even in small deforested areas.

It was noted (Salati *et al.*, 1983a) that in small clearings there is likely to be little measurable effect, because the drier air will be swamped by moist air from surrounding forest. However, the recycling of water will have been reduced by a small amount, and the effect of a great number of small clearings could in aggregate be very large. Deforestation of large areas, say greater than one kilometer and less than one hundred kilometers in diameter, should result in a significant reduction in water returned to the atmosphere, diminished local cloud cover and an increase in solar radiation. Precipitation due to local recycling is likely to be reduced.

Reduced local precipitation could have severe effects in central Amazon, where there is already a distinct dry period. If a relatively small reduction in annual rainfall resulted in an extension of the dry period there could be serious consequences. Fearnside (1982) noted that in Manaus in 1979 there was a period of 73 days without rain. If this became common, then inevitably there would be marked ecological changes. There have been a number of attempts to model the effect of Amazon deforestation on precipitation and temperature, and we have recently reviewed them (Salati and Vose, 1983b and c), and concluded that the Henderson-Sellers (1981) suggestion of a decrease in rainfall of 600 mm yr^{-1}, and a small temperature increase is most valid of the current predictions.

Within Brazil, reduced precipitation in Amazon could mean that less water vapour was available for export to Central Brazil i.e. the cerrado area. Marques *et al.* (1979, 1980) determined from radiosonde studies that water vapour is exported south from the Basin to Central Brazil and to the Chaco Paraguaio in almost every month of the year, but principally in March and December. Less rainfall in these areas could have consequences for cropping.

As Amazon accounts for 30% of the land area of the 20° Equatorial belt it has, together with the Congo region, a marked degree of continentality. Thus large changes of land surface cover in these areas due to deforestation could affect regional climates. In such large scale studies it is necessary to consider the influence of the variation of the quantity of water vapour which condenses in the higher parts of the atmosphere, as it is during evaporation that solar energy is transformed into latent heat and is released in the highest layers of the atmosphere where the water vapour condenses to form clouds. This energy is partly responsible for the circulation movements of the upper atmosphere, while part of the water vapour is transferred to the polar regions, where upon condensation it releases energy. This serves to transfer energy from the equatorial to polar regions. Estimating the climatic consequences of deforestation on a continental or global scale involves many problems, as recently emphasized by Wilson and Henderson-Sellers (1983).

Despite past suggestions (Newell, 1971) that Amazon deforestation might affect the atmosphere general circulation, the present general consensus seems to suggest (e.g. Dickinson, 1981) that tropical deforestation, while it might cause local changes, is not likely to cause global climate change greater than due to natural climatic fluctuations. However, the consequences of deforestation on the climate, whether micro-, meso- or macro-, is still an open question.

More data from remote sensing of general weather patterns, better and more detailed information of water vapour circulation patterns at local level, and improved modelling studies should eventually remove some of the uncertainty. In the meantime, the likelihood of at least local disruption of hydrological cycles seems sufficiently great that a conservative approach to tropical deforestation seems highly desirable.

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