Spatial and Temporal Patterns of Amazon Rainfall

Author(s) : Wim Sombroek
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Consequences for the Planning of Agricultural Occupation and the Protection of Primary Forests

INTRODUCTION

The current efforts for ecologic-economic zoning within the Amazon region, as for instance carried out for the Brazilian part under the patronage of the MMA/PPG7/SPRN project (1), require information on the spatial variation of climatological characteristics as one of the criteria.

Until recently the only climatological data available were those of the fully equipped meteorological stations in the region that have at least 30 years of continuous recording (50 stations, of which 30 in the Brazilian part).

These stations are located by-and-large along the major rivers and are therefore not necessarily representative for the upper catchments. A much larger network of simple pluviometric stations, about 800 in total, has been operational in the Brazilian part of the Amazon region since the 1970s. The network is fairly evenly distributed over all subcatchment areas. It has been suggested that rainfall conditions away from these rivers are substantially different. An analysis has been made of the records of a network of simple pluviometric sites in the Brazilian part of the region as maintained by the National Agency for Electric Energy (ANEEL) since 1970. The latter data sets were used to draw more detailed maps on annual rainfall, and on the strength of the dry season in particular; average number of consecutive months with less than 100 mm, 50 mm, and 10 mm, respectively. Also, some data were obtained on the spatial expression of El Niño events within the region. Sub-regional differences are large, and it is argued that they are important for the success or failure of agricultural settlements; for the hazard of large-scale fire damage of the still existing primary forest vegetation; for the functioning of this land cover as stock and sink of CO₂, and for the likelihood that secondary forests on abandoned agricultural lands will have less biomass. The effects of past El Niño rainfall anomalies on the biodiversity of the natural savannahs within the forest region are discussed.

MATERIALS AND METHODS

The study area was demarcated based on hydrographic, vegetational and legal considerations. It concerns the areas of the Amazon river basin downstream of the Andean Cordillera, the Araguaia-Tocantins basin, the minor catchments directly bordering the Atlantic ocean, as well as the river systems of the Guyanas and southern Venezuela. The vegetational criterion is the Amazon humid tropical forest biome, including its internal edaphic savannahs. Legally, it concerns the 9 countries of the Amazon Cooperation Treaty, and the 9 states of Brazilian Amazonia Legal. The total area is about 6 x 10 km², which is equivalent to the size of Europe, excluding Russia.

The digitized topographic base map of Amazonia Legal, scale 1:3 000 000, of the Brazilian Geographic and Statistics Institute (2), was used as cartographic base. The western and northern edges were taken from a map of the World Meteorological Organisation (WMO) (3). Areas above 500 m altitude are indicated on the maps with a shading, on the basis of various cartographic sources. The location and data of full meteorological stations of long-term functioning in the Brazilian Amazon were taken from various publications of the National Meteorological Institute INMET (4). The non-Brazilian stations were taken from the WMO database (3). The total number of stations is about 50, or 1 per 120 000 km².

The network of simple pluviometric recording sites within the Brazilian Amazon—about 800, of which about 700 within the forest zone—was copied from draft maps of the Rede Básica Hidrometeorológica Nacional, which is maintained by the National Agency of Electric Energy (ANEEL, formerly DNAEE) on the basis of field recordings carried out by institutions such as CPRM (Geological Service) and IDESP.
(Socio-economic Development Institute of Pará State). The Hydrologic Resources Department of ANEEL kindly provided all computerized pluviometric recording data, on a monthly basis, for all of the Brazilian Amazon. Such pluviometric information networks also exist for the Amazon parts of neighboring countries, but they are of much lower density, except for the Guyana’s, and their data were not available to the author.

There are 2 types of fully equipped meteorological stations. Those qualifying for the 30-year averaged “normals” criterion of WMO (full periods 1930–1960 and 1960–1990) are indicated with large black dots within circles, while those that do not have recordings of sufficient length, gauge, or reliability to be used statistically are indicated with large black dots without circles. The recordings of the simple pluviometric sites are of varying quality. Some are quite long-term, having started around 1965 and continued uninterruptedly till 1998. Others started recently or have been abandoned 10 to 15 years ago. Those sites with less than 10 years of recording, and/or low reliability—gaps in the monthly data or obvious anomalies—are indicated on the maps with small open dots, the others with small black dots. The poor accessibility of higher-altitude and broken landscape situations of the Guyana and Brazilian Shields, and the occurrence of Indian Reserves—which often coincide with high and inaccessible terrain—have resulted in several subareas of poor or nonexistent rainfall recording sites. Examples are the whole frontier zone of the Guyana’s with northern Pará, and the interfluve zone between the Araguaia and the Middle Xingu rivers.

Interpolation lines of annual and monthly rainfall characteristics were drawn manually, taking into account the variation in reliability as described above. To a degree, the hydrographic pattern was taken into account, once it became apparent that away from the main rivers and their broad floodplain the annual rainfall is higher and the dry season less pronounced than near these rivers, in agreement with a hypothesis of Molion and Dallarosa (5). This “Manaus rule” or brisa fluvial is defined as the effect of local river breeze circulation away from the waterbodies, due to early-daytime preferential ascending cloud formation over the forest-covered land area. It apparently holds true for the stretches Solimões – Meio Amazonas – Baixo Amazonas, but is replaced by a contrasting rule for the very wide water-bodies at the mouth of the river system, where the tropical Atlantic ocean causes high annual rainfall but a pronounced dry season. This is called “Marajó rule” or brisa do mar (6). In the southeastern part of the region the parts of higher altitude (above 500 m) appeared to have somewhat higher annual rainfall and lower dry-season strength. This phenomenon was subsequently used in the fine-tuning of interpolation lines.

Interpolation lines for the non-Brazilian parts of the region are very tentative. They are based on the WMO (3) map on annual rainfall, while for the seasonal characteristics use was made of the Length-of-Growing-Period (LGP) approach of FAO (7) and its database on monthly rainfalls. Also a French study (8) on the geography of the rainfall in the Guyana’s and southern Venezuela was taken into account.

Computer-driven kriging of the interpolation lines was not attempted, because both the reliability categories of the recording stations and sites, and the influence of large waterbodies or orographic features are as yet too vague to be put in formal
weight classes. However, gridding of the pattern that results from the present manual interpolation is probably a relatively simple exercise for ecosystem modelling specialists. Translation of the map pattern into the Köppen or Thornthwaite climatic schemes is feasible as well.

Four different digital maps were prepared (Maps 1–4):

Map #1: annual rainfall pattern, with isohyets of the WMO system: 4000, 3600, 3200, 2800, 2400, 2000, 1600, 1400, 1200 and 1000 mm, and 2 extra isohyets in the lower range: 2200 and 1800 mm.

Map #2: the number of consecutive dry months, averaged over the years of observation, with 100 mm monthly rainfall as criterion.

Map #3: number of consecutive dry months, averaged over the years of observation, with 50 mm monthly rainfall as criterion.

Map #4: number of consecutive dry months, averaged over the years of observation, with 10 mm as criterion, also implying a low atmospheric humidity during the dry months.

In all 4 cases the central month of the dry season is indicated, but without line boundaries.

The set of 3 maps (Maps 2–4) on the characteristics of the dry season is rather uncommon. Many studies on the Amazon climate provide maplets with isohyets of selected dry months, for instance July and December, but examples of the integration of all dry months providing quantitative information on the length, strength and regularity of the whole dry season are very few. The Length-of-Growing-Period map of FAO (7) at scale 1:5 000 000 shows, understandably, the wet season instead of the dry one.

A recent NGO study on the risks of forest fires (9) recognizes the importance of the dry season, but does not show it in map form, though it refers to an attempt on gridded input in a NASA-CASA ecosystem production model (10). Characterizing a dry month as having less than 45 mm rain, it used only the normalized 1961–1990 records of the recognized WMO meteorological stations for the whole of Brazil. An early attempt was made by the present author (11), applying the 100 mm month$^{-1}$ and 50 mm month$^{-1}$ criteria to the recordings of the 25 meteostations available in 1959 (12).

Attention was given to the occurrence of years with exceptionally low rainfall, which would give indications of local influence of the El Niño phenomenon. However, the relatively short length of many of the pluviometric records did not allow for delineation of spatial drought patterns with any degree of accuracy on an additional map.

RESULTS

The use of the computerized pluviometric database of ANEEL yields a more detailed pattern of annual rainfall (Map #1) for the Brazilian Amazon, when compared to published maps (3, 13, 14) and a number of page-size maps in review articles (15–18). The annual rainfall away from the main rivers is higher. The spatial pattern is complex, not only in the water-divided areas where orographic unevenness may have an influence, but also in homogeneously low altitude areas. An example is the configuration for Marajó island in the mouth of the Amazon river. A far more intricate pattern was found than assumed thus far: less rain-
fall in its western interior part without a dry season, contrasting with high rainfall on its coasts, but partly with a pronounced dry season. Areas with low annual rainfall (< 1800 mm) occur in Roraima, the upper Trombetas-Jari area of northern Pará, southwest of Altamira on the Trans-Amazonica, and the Açailândia area on the frontier Pará-Maranhão. Together they constitute a sort of dry belt or corridor. However, these are also the areas with relatively low-density field information, and many of their recording sites have moreover become nonoperational.

The bulge of dryness in the Paragominas-Açailândia area, with its high degree of deforestation since the early 1960s, is noteworthy. During the combined forestry- and soil survey of FAO in 1960/61, when the primary forest coverage was still complete, both the high timber volumes per ha and the low base saturation status of the soils in the Paragominas area suggested that in those days the dry season was little pronounced. Only 200 km south of Paragominas town the timber volumes dropped below 100 m³ ha⁻¹ and the base saturation of the soils reached levels above 35% (19), indicating a strong seasonal drought. It is possible that the strength of the dry season and its duration have become more evident because of the large-scale deforestation. However, records of the Paragominas meteostation—started only in 1965 and out of operation since 1995 because of lack of municipal interest—do not show such a negative trend. Any tendency to decreasing rainfall in the region after large-scale deforestation may be verified easier in northern Mato Grosso or central Rondônia where pluviometric records are of longer term.

An indirect indication of a negative effect of large-scale deforestation on the amount and regularity of subregional rainfall is given by the 2-lobed extension of drier conditions in the Barcelos-Rio Branco area in the south of Roraima State. The abundance of edaphic white-sand savannahs there would imply reduced evapotranspiration, hence less cloud formation in the dry season.

Screening of the 800 individual pluviometric records; analysis of the data of the full Brazilian meteostations—the first ones dating from 1910—as well as scanning of the oscillations in the discharge regime of the Rio Negro-Rio Solimões system at Manaus, measured since 1902 (20, 21) give the following indications on El Niño occurrences since 1900:


The ANEEL data set provides also some information on the spatial variation in the strength of the El Niño phenomenon within the Amazon region. The central-northern zone apparently experiences stronger El Niño effects than the southern zone. In the north, the dry season has a gradual start and an irregular length (“wobbly” character); in some years there are one or more completely dry months outside the long-term average period, which has its center in January. In the south, the dry season starts quite regularly and abruptly, with the center in July–August (southwest) or September (southeast). The dry season in the eastern part of the Brazilian Amazon, near the ocean coast, is transitional between the 2 systems, with its center in October.

**CONSEQUENCES FOR ECOLOGIC-ECONOMIC ZONING**

The new set of rainfall maps can be used in various ways. In their present vectorized form they have applications at regional, state and municipal levels. In a gridded and digital form, they can be helpful in modelling biosphere processes for the region as a whole, in different scenarios of human occupation and climate change. Gridding with 30’ x 30’ latitude/longitude for global models, or at 5’ x 5’ pixels for Amazon-level models (10) may want to combine the data of Maps #2, #3 and #4 through a composite legend.
The map on annual rainfall (Map #1) is relevant for hydrological studies as it provides information, together with the existing ANEEL set of fluviometric data, on the minimum, average and maximum water flows of subcatchment areas. These are of use for the planning of road constructional work, for river traffic, groundwater recharge, aqueous pollution control, urban-center water supply and sanitation discharge, local hydropower generation, etc.

For agricultural and ecological studies, the dry-season Maps (#2, #3, and #4) are more important. Viability and sustainability of agricultural settlements, forest biomass growth, risks of forest fires, chances of forest recuperation, atmospheric carbon sequestration, supplementary soil moisture storage, and El Niño effects in ecological tension areas will be discussed here.

**Agricultural Settlements**

Building of rural access roads and their maintenance is much less problematic when there is a distinct dry season. The same holds for infrastructural facilities at the settlement centers, whether such centers are oriented on agricultural produce, or engaged in mining, logging or non-timber forest product gathering. Human and animal health is favored by a dry period, restricting the spreading of endemic diseases and the multiplication of their vectors. Even more significant for the viability and sustainability of agricultural settlements are the dry-season effects on land clearing practices and crop growth. In the absence of a dry season (the 0 and 1 dry-months zones under the less than 100 mm month⁻¹ criterion; Map #2) the burning of primary or secondary forest vegetation after complete slashing remains incomplete. This makes the newly cleared land surface less suitable for the planting of food or cash crops or the implantation of pastures. Crops such as upland rice, maize and beans need a dry spell for ripening and hardening of their grains, and the prevention of rotting after harvesting. The yield of such crops is anyhow bound to be lower because the near year-round cloud cover implies lower daylight intensities, hence lower photosynthesis. This is also reflected in the 365⁺ isoline of length-of-growing-period maps of FAO (7, 22). The above restrictions hold even more for large-scale soybean growing. This crop is sensitive to attacks by a number of diseases and pests in its vegetative stage if near-surface air humidity remains high during a good part of the day, such as in the edaphic savannah area of Humaitá. The use of heavy machinery at the required high degree of mechanization for the crop to become commercially viable, is only feasible when the land surface is reliably dry at both planting and harvesting times. Only zones 1, 2 and 3 of Map #4 (which uses the 10 mm month⁻¹ criterion) are therefore suitable for mechanized soybean cultivation. FAO recognizes a growing period of only 120 to 300 days as suitable to very suitable for the crop (7).

Suitable food crops in the continuously moist regions are cassava, bananas, and certain tree-fruit crops (23, 24). The health of cattle, for household use or meat commercialization, is problematic in near-constant rainy conditions because of abundance of ecto-parasites and blood-sucking insects (25), as well as nutrient imbalances in the soils (26) and long distance to markets and supply centers. It is noteworthy that the zones 0 and 1–2 of Map #2 coincide with the near absence of sustained agricultural settlements of substantial size. Whether government-organized or spontaneous, many recent settlements in these zones have been abandoned. This is not clearly indicated on Remote Sensing based maps of deforestation areas, because they do not normally distinguish between active settlement and frequency of old regrowth. There are indications, from the denseness of patches of terra-preta-do-indio soil (11) and early historical records, that the pre-Columbian Amerindian populations also preferred dry-season areas—unless soil and river-strategic conditions were particularly favorable.

The largest areas with active deforestation for agricultural purposes and permanence of rural settlements coincides with Zone 5 of the 100 mm month⁻¹ Map (#2), as confirmed by Landsat-TM imagery, by the áreas antrópicas of the 1995 IBGE map on Amazônia Legal (2) and the network of feeder roads on the present maps. These are apparently the areas where one or two crops per year, and several perennials, have secure yields. Among the commercial perennials, only oil palm thrives in the permanently humid zones, as proven by several successful plantations near Belém. The lack or neglect of processing facilities has thus far been an impediment for sustainable oil palm enterprises in government-led efforts in Amazonas state (Tefé; Distrito Agropecuario north of Manaus). Rubber plantations have been a failure nearly everywhere in the region, because of their sensitivity to the Dothídella ulei fungus. A FAO/UNDP committed study by the Agronomic Institute of Campinas (27) concluded that only areas with a distinct dry season and a low-temperature spell would be safe niches for rubber plantations. The southern higher-altitude areas, indicated with a shading on the present maps, would therefore be of potential interest for rubber plantations.

**Timber Volume, Biomass Productivity, and Carbon Storage**

Early FAO forest and soil inventories (11, 28), the more recent RADAMBRASIL multidisciplinary inventories (29) and their spatial generalization (30), all indicate that the highest gross timber volumes and thus aboveground biomass values, $> 200$ m³ ha⁻¹ implying $> 100$ tonnes C ha⁻¹, occur in areas where the total annual rainfall is about 2000 mm and there is a dry season of 2 to 3 months (50 mm criterion) and 4 to 5 months (100 mm criterion), respectively. These are also the areas preferred for agricultural settlement, especially where the soil conditions are favorable, as is the case for the diabase- or limestone-derived dusky red soils near Altamira and the high base status soils in Rondônia. Safeguarding the remaining forest patches in such areas, as permanent ecological reference sites, should be given high priority in the “hot spot” approach to tropical forest conservation.

Forest growth apparently benefits from a short dry spell, possibly because of smaller damage from diseases and pests. Probably more important is the lower interception of sunlight, an essential plant growth factor, in comparison with the near-continuously cloudy areas. Modelling of the potential Net Primary Productivity of biomass (NPP), based on remotely sensed average cloud cover as derived from NDVI-AVHRR data sets of NASA, gave NPP values of 1000–1200 g C m⁻² yr⁻¹ for the continuously moist zone vs. 1200–1400 g C m⁻² yr⁻¹ for other parts of the region (10).

Timber volumes are lower and the chances for high-forest recuperation are poorer when soil conditions in the short-dry-season zones are marginal (shallowness; compactness of the subsoil, swell-shrink behavior, or extreme sandiness). Under such conditions anthropological disturbances, whether present-day or from pre-Columbian Indian population groups, will result in bamboo forest (bambozal) of Acre and adjoining parts of Amazonas (31); creeper-and-vine forest areas (cipóalas) of the lower Xingu planalto stretches (11, 32); Orbignya palm forest (babazuualas) in the middle Xingu area (32, 33), or even shrub savannah (campinas) areas near Santarém and Manaus. All are divergent vegetation types, with lower stocks of carbon and often also lower biodiversity than the closed-canopy high forest.

**Forest Fires and Forest Recuperation**

As demonstrated by the 1997/98 extensive forest fires in Roraima state, there is a large spatial variation in the risk of forest fires, which may spread from slash-and-burn sites or are caused by lightning. Fire risks are low if logging takes place very selec-
tively for rare precious timber or with careful planning for long-term sustainable yields of more tree species, say only 30 m$^2$ ha$^{-1}$, once in 20 years or so (34). If higher volumes are cut and towed away then the remaining off-fall can become a source of easily flameable dry matter, augmented by litter from semi-deciduous species where the dry season is pronounced. The resulting below-canopy fires often remain undetected by radar- or visual-light-based Remote Sensing, but may cause considerable damage to floral and faunal diversity (9).

The chances for “accidental” extensive forest fires are largest in the zones 5 and 6 of the 100 mm Map (22), and the zones 3 and 4 of the 50 mm Map (23). Variation in soil conditions, especially the moisture storage capacity, plays a modifying role.

It is generally assumed that it will take 300 to 1000 years before a completely burned-down humid tropical forest regains its original structure and species composition (35). However, recuperation to a high, closed or open-canopy forest is far from sure, as demonstrated by several field studies (36). As soon as there is a long dry season and soil physical conditions are poor, recuperation becomes unlikely. Zones 1, 2 and 3 of Map #4 (the 10 mm month$^{-1}$ criterion) with their very pronounced dry season are areas where the primary forest, already semideciduous, is a relict from former, more humid climatic conditions. It will never regrow to its present status if subjected to large-scale slash-and-burn practices for ranching or soybean cultivation. There are, however, several large Indian Reserves in these zones that may provide protection from massive deforestation.

**Carbon Sequestration Potential**

The Amazon forest ecosystem is a large store of carbon. Until recently it was assumed that in mature forests the uptake of atmospheric CO$_2$ for daytime assimilation is balanced by an equal-strength CO$_2$ emission through nighttime canopy respiration and heterotrophic soil respiration. Only young secondary forest would act as a CO$_2$ sink. However, studies in Rondônia (ABRACOS project in the Ji-Paraná area (37)) and north of Manaus (BIONTE project (34)), using eddy-correlation flux measuring techniques from towers in old-growth forest and partly also tree-girth measurements, suggest otherwise for recent years. Apparently the increased CO$_2$ concentration in the atmosphere stimulates tree growth, resulting in a net uptake, called sequestration or sink condition for CO$_2$, by the forest ecosystem in the long run. It is more likely that a good part of the generated higher biomass will end up in the forest soil, in the form of higher soil organic matter content of a stable nature. Soil organic matter is already nowadays a very significant stock of carbon (41–44). Increased above- and belowground tree growth implies earlier maturity and thus earlier senescence, hence higher tree fall intensity and associated higher input of organic material over the rootable depth of the soil.

There are indications that the function of the Amazon primary forest as a CO$_2$ sequestering mechanism is interrupted during El Niño years. It has been suggested that there would be insufficient soil moisture reserve in such years (45), thus moisture rather than CO$_2$ concentration becoming the limiting growth factor. In contrast, the Net Primary Productivity in those areas that are normally without any dry season, such as west of Manaus, may benefit from an El Niño year because of the temporary availability of more sunlight for photosynthesis.

**Soil Moisture Storage**

At the beginning of the dry season, plant growth can continue unabated for some time because of a reserve of moisture in the rootable soil. However, the plant-available moisture storage capacity (PAM, moisture in the suction range of pF 2.0–4.2) of the various Amazon soils is poorly quantified. There is an acute scarcity of direct measurement of soil moisture suction characteristics on undisturbed samples and of their bulk densities. The few hard data carried for Brazilian soils are summarized by Tomasella and Hodnett (46). About 30 of the profiles with pF data are from the Amazon region itself, mainly from Para State and the neighborhood of Manaus, where Xanthic Ferralsols (Lotossolos amarelos) predominate. There are no soil profiles with pF data for the Brazilian or Guiana Shield areas, nor for the vast area (700 000 km$^2$) southeast and east of Manaus that has fine sandy to silty sediments of the Late Pleistocene Igá formation and Plinthic Acrisol as main soil (47). Xanthic Ferralsols and related soils are deep but are known to have low values of PAM, viz. 5–10 vol.% in the central and lower parts of the profiles, even if they are very clayey. Hydrologically, they act like sandy soils of temperate regions. Less weathered soils of the Amazon and Brazil-at-large, such as Orthic Acrisols, Luvisols and Cambisols have substantially higher values, viz. 10–15 vol.% and even more in topsoils when rich in humus, but these soils are less deep.

Comparison of analytical data on disturbed samples with texturally equal, but mineralogically different temperate-zone soils will give too high PAM values. Special equation calibration is required (48) to arrive at estimates that are in line with the few existing pF data. The overestimation problem is also pointed out in the recent NGO study (9) on fire and deforestation risks. The study could not use the RADAMBRASIL data set of 1147 analyzed soil profiles of the Brazilian Amazon (29) for comparison with soil textural situations of temperate zones because none of these profiles have pF or bulk density data. An additional problem is the relevance of the maximum soil moisture-suction value for the humid tropical forest environment. The internationally used value of pF 4.2 (15 atm. suction) was established for the wilting point of temperate-zone annual crops such as sunflower and wheat. It is possible that tropical forest species have smaller suction force, but this was never investigated, either in the field or in laboratory growth chambers. With respect to maximum photosynthesis and CO$_2$ uptake, the leaf stomata should be fully opened during daytime. Therefore, the more readily available moisture (pF 3.5 minus pF 2.0 values), which may be only two-thirds of the PAM value, should be the really important amount at modelling of the carbon sink function of the forest.

The total moisture availability for uninterrupted plant growth is a combination of the PAM value per soil horizon and the total depth of the soil that is rootable. Total rootable depth varies highly over the Amazon region, from extremely deep (5–10 m) on the freely draining Xanthic Ferralsols (49, 50), to quite shallow (50–100 cm) for many of the Plinthic Acrisols southwest of Manaus with their relatively low timber volume (43). The
ABRACOS project monitored at weekly or half-weekly intervals for 2 to 4 years the moisture content till a depth of 3.6 m under forest and planted pasture, at 3 sites (north of Manaus; Ji-Paraná in Rondônia, and Marabá in southern Pará State) (51). Soil moisture abstractions at all depths were much greater under forest than under pasture, and also deeper, well into the weathering substratum. Per soil horizon there was a much smaller abstraction in the Ferralsols than in the other 2 soils, which is consistent with its assumed lower PAM values (no pF curves established).

It can be concluded that forests on Ferralsols, when a distinct dry season is present, need to root deeper to secure sufficient soil moisture for uninterrupted growth than those on less weathered soils. In general, representativeness of analyzed soil profiles for broad landscape-related soil units, rather than indiscriminate statistical analysis of the total number of samples, should be used to arrive at spatially improved estimates on effective depths and moisture storage capacities for forest growth, including validation by measurements on undisturbed samples (51).

El Niño and Ecotonal Biodiversity

Among the El Niño occurrences in the Amazon as listed above, the period 1925–1927 stands out. More than a full-year drought occurred in the Rio Negro catchment area, with many forest fires and extremely low river-water levels that impeded river travel. This event is well documented in a report by the Salesian bishop of the area to the Vatican (52).

Very strong El Niño events such as the 1925–1927 one will have occurred earlier as well, perhaps at intervals of 70 years. There are reports (24) of very strong droughts in 1860 (Purus area) and in 1774 (Rio Negro area). They must have had pronounced effects in ecotonal field situations at the edge of the forest biome, and in areas of ecological tension within the system. The latter would apply, for example, to the edaphically determined patches and stretches of savannahs and savannah-forests, which are particularly frequent in Amazonas state (campos, campinas, campinaranas, caatinga amazônica). Their present-day specific biodiversity, including endemism, and their vegetational structure—both not well studied thus far—would be impacted in such exceptionally dry years (53). Physiological drought effects would be enhanced by accidental fires, or purposely started ones by Amerindians or early settlers, resulting in sharp boundaries with the surrounding forest.

From studies on charcoal occurrences in the São Carlos do Rio Negro area (54) it was concluded that extensive fires must have occurred 250 to 400 years ago. Still larger effects will have had the very broad-periodicity prehistoric “Mega El Niño’s” recognized by Meggers (55, 56) on the basis of pollen sequences and river-level fluctuations in the northern part of the region (stone-grinding sites of Amerindians are occurring below present-day low-water levels of rivers). She identified dry periods around the years 400, 700, 1200 and 1500 BP. The occurrence of 3 levels of broad low terraces of the Late Pleistocene Ica-formation in western Amazonas (47) suggests that also before 1500 BP there were times with lower rainfall and/or stronger dry seasons, succeeding an overall wetter period between 12000 and 5000 BP (17).

An example of sharp vegetation boundaries induced by fire is the large forest-encircled open savannah area in southeastern Amazonas state, below the southern dip of the Trans-Amazonic highway. It is a surmised source area of the Tupí groups of Brazilian Shield area. Their present-day specific biodiversity values of the many intraforest natural savannahs merit additional study, also in relation to past and present El Niño droughts and early Amerindian land-use activities.

CONCLUSIONS AND RECOMMENDATIONS

Interpolation of the data of simple pluviometric recording sites away from the main rivers is helpful in assessing and mapping the spatial variation in annual rainfall, as well as the length, strength and regularity of the dry season in the Amazon region. The dry season characteristics are important for the success or failure of agricultural settlements, the variation in aboveground biomass, the risk of forest fires, and the chances for forest regeneration. They also provide information on the extent of the CO₂ sink function of the primary forest, as well as the spatial variation and strength of El Niño drought anomalies. All of these factors need to be taken in consideration with the current efforts to establish national and state-level policies for forest protection in harmony with sustainable rural settlement.

Many of the pluviometric recording sites in the Brazilian part of the region have recently become nonoperational. For the benefit of agro- or forest-ecological and socioeconomic zoning purposes at subregional or municipal levels, it is recommended that this situation be remedied soonest, and that extra sites be established in the so-called dry corridor of the eastern part of the region. At the same time, several fully automatic and satellite-linked complete meteorological stations should be established and maintained in remote water divide areas, to substantiate the information from the pluviometric network.

There is a great need to correlate rainfall patterns with data on key soil physical parameters, with specific attention to measurement of total rootable depth, bulk density and net soil moisture storage capacity, in actual field situations and on undisturbed samples at laboratory analysis. These properties need to be determined also for the deeper subsoil and the weathering substratum, particularly in areas where there is a long dry season. The resulting Amazon soil moisture storage map should be linked with the 3 dry-season maps (Maps 2–4), to arrive at quantitative estimates of the occurrence of a “CO₂ sink” function of the Amazon old-growth forests, spatially from per-humid to semi-deciduous and temporally in and between El Niño years. One of the outcomes may be that the sink function is more substantial and continuous in the zone with little or no dry season, like most of the state of Amazonas and the adjoining parts of Peru and Colombia, even though this zone does not have the highest timber volume at present. They would then qualify even more for protection through the Ecological Corridors idea of the PPG7 program.

Quantifying the spatial and temporal carbon sink function of the forest also requires that the network of CO₂ flux monitoring of the ongoing LBA program be extended to areas beyond the axial zone Manaus-Santarém-Belém, to incorporate different rainfall and soil conditions in western Amazonia and in the Brazilian Shield area.

The origin and the specific biodiversity values of the many intraforest natural savannahs merit additional study, also in relation to past and present El Niño droughts and early Amerindian land-use activities.
References and Notes


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30. A CD-ROM with the digital version of the four maps may be obtained from the GTZ office at IPAAM, Manaus <gtz@ipaam.br>.


Wim Sombroek holds a PhD in agricultural and environmental sciences from Wageningen University. From 1959 to 1979 he participated in tropical soil survey and land evaluation projects in Latin America (Brazil, Uruguay) and Africa (Nigeria, Kenya). From 1979 till 1991 he was director of the International Soil Reference and Information Centre (ISRIC) in Wageningen and during those years he also served as Secretary-General of the International Society of Soil Science (ISSS), a scientific associate of ICSU. In 1991, he became Director of the Land and Water Division of the Food and Agriculture Organization of the United Nations (FAO) and was its focal point on Climate Change matters. He retired from the FAO in 1996 and then accepted an invitation from GTZ to become a team member/consultant in a Manaus-based project on natural resource policies, under the Pilot Programme for the Brazilian Tropical Forests of the G7 countries and Brazil (PP/G7). His address: ISRIC, P.O. Box 353, 6700 AJ Wageningen, The Netherlands. E-mail: sombroek@isric.nl