The Biome Distribution in Amazonia and Climate

CARLOS A. NOBRE

Center for Weather and Climate Forecasting - CPTEC,
Instituto Nacional de Pesquisas Espaciais - INPE 12643-000 Cachoeira Paulista, SP, Brazil

ABSTRACT

Climatic observations of Amazonia and the detailed study of the water and energy cycle over forests and pastures in Amazonia (ABRACOS Project) are used to propose a simple biogeographic model of the biome distribution in tropical South America, for the forest and savanna biomes. In this simple model the boundary between forest and savanna is primarily driven by the availability of soil moisture to the roots of the vegetation, therefore, directly linked to the duration of the rainy season.

INTRODUCTION

The accepted bioclimatological view maintains that rainforests can exist only in high rainfall tropical areas, having short or nonexistent dry seasons, where soil physical properties ensure high levels of available soil moisture throughout the year. On the other hand, the mechanisms giving rise to semicontinuous and high rainfall rates throughout the year for those regions were thought to be due solely to the general circulation of the atmosphere and not dependent on the underlying vegetation (Nobre et al., 1991). A number of numerical experiments has changed this view. Presently it is believed that the current climate and vegetation coexist in a dynamic equilibrium that could be altered by large perturbations in either of the two components.

Tropical forest is one of the most important, yet least studied, ecological systems of the world. The importance of tropical forest in determining the global water and carbon balances, and the world's resources of animal and plant species is well-recognized. The difficulties of working in tropical forest have limited the research. Replacing forest by pasture, the interaction between soil, vegetation and atmosphere changes. If large areas are deforested we can expect changes in the weather systems and climate.

Deforestation was rapidly progressing in Amazonia during the 1980's. In Brazilian Amazonia, the average annual deforestation was 21.000 km2 from 1978 to 1988. During the late 1980's and early 1990's deforestation rates have diminished. The latest available figure for 1991 showed the deforested area to be about 11.000 km2. The total deforested area was 435.000 km2 (about 11.5% of the total forest area). Given the apparent unpredictability of societal actions and behavior, it is impossible to predict whether the current high rates of tropical deforestation will decrease, or even increase, in the future. On the time scale of one to two decades, the already-existing pressures on the tropical forests, especially in Amazonia, will keep deforestation at high levels. Any major decline of tropical deforestation is not expected, given the development policies of the Amazonian countries. One question that arises is whether the large-scale deforestation in Amazonia might affect the regional climate, with consequent implications for the biota in the region.

The prediction of the impacts of complete Amazonia deforestation has been investigated by means of a number of General Circulation Models (GCM) simulation experiments. In these experiments the model's vegetation over the whole Amazonia is changed from tropical forest to grass (pasture). The predictions show too many uncertainties to render them as quantitatively accurate or reliable of post-deforestation climate *even* if complete deforestation scenarios were realistic. However, the models are, in general agreement, of a post-deforestation climate with higher surface temperature, less evaporation and less precipitation for Amazonia, although there are large discrepancies in the magnitude of the predicted changes. Additionally, even assuming basin-wide deforestation scenarios, little can be said about remote climate impacts of Amazonia deforestation. Quantitatively the predictions indicate an air temperature increase in the range 1 to 2.5 C, a reduction of evapotranspiration of 0.5 to 1 mm/day and a reduction in precipitation between 0.3 to 1.5 mm/day. All predicted changes are exacerbated during the dry season, that is, increases in air temperature are even higher, as are the decreases in evapotranspiration and precipitation. These results suggest that a complete and rapid destruction of the Amazon tropical forest could be effectively irreversible in the areas surrounding Amazonia. Changes in the region's hydrological cycle and the disruption of complex plant-animal relations could be so profound that, once the tropical forests were destroyed, they might not be able to reestablish themselves.

Reconstruction of the paleoclimate record shows evidence of periods with a drier, colder climate for the Amazon, such as during the peak of the last Ice Age. The tropical forest retreated considerably and much of Amazonia was covered by savanna, indicating that the forest-savanna boundary responds to the external forcing provided by the general circulation of the atmosphere over very long time scales. Interannual variability of precipitation in Amazonia is large, as revealed by the river streamflow record. A large part of this variability is linked to El Niño-Southern Oscillation (ENSO) events. During severe dry spells in Amazonia, extensive forest fires can occur. These infrequent, intense and long dry spells are usually linked to the simultaneous occurrence of intense ENSO episodes. However, the forest appears to be adapted to withstand these large interannual variations in precipitation and the sporadic occurrence of forest fires. Even at the boundaries of the forest where the interannual variability is more pronounced, migration of the forest border is not observed (Nobre et al., 1991).

Next we review the observations of evapotranspiration and soil moisture provided by a recent research experiment carried out in Amazonia since 1990. These observations form the basis to propose the simple biogeography model in the last section.

ABRACOS RESULTS

ABRACOS — the Anglo-Brazilian Amazonian Climate Observation Study - is a research project whose main objective has been to improve the predictions of how changes in the hydrological cycle brought about Amazonian deforestation affect climate.

The aim of ABRACOS was thus to collect datasets for forest and the cattle ranchland which was replacing the forest. At the same time continuous measurements of climate and soil moisture were initiated to look at the long term differences between forest and existing clearings. These pairs of stations (forest and pasture) are producing data which can be used to test the formulations in GCMs to see how well they model the current climate, and the changes which might occur following deforestation.

ABRACOS has three experimental sites across Amazonia: clearings and forest areas close to Manaus, in central Amazonia, near Marabá, in the state of Pará, close to the eastern edge of the forest, and near Ji- Paraná, in Rondônia, close to the south western edge. These last two sites are in areas where there is a longer and more pronounced dry season than around Manaus. This gives greater soil moisture stress and therefore the opportunity to study the behavior of forest and pastures over a wider range of conditions.

Here the main results of ABRACOS are summarized (see the list of references, from which these results were drawn).

The pasture reflects more solar radiation than forest, although the difference is less than it was previously thought, and there is a seasonal variation in the reflected percentage. This gives more energy available for the forest to evaporate water.

During wet conditions the proportion of energy used for evaporation by forest and grass is similar. In the dry season forest evaporates more water. It has deep roots, down to at least 4 m, which can access a large reservoir of soil water.

The response of surface conductance to the environment is different for forest and pasture. These differences have been modeled. Differences in leaf area and the capacity of the soil to hold water must be taken in account when extrapolating the results to other sites.

The compactation of the soil during and after forest clearance reduces the ability of the soil to drain water; but, provided that bulldozers are not used, the effect is limited to the top 20 cm and is quite variable.

The atmospheric boundary layer is much higher over areas with substantial clearance than over adjacent forest. This demonstrates how multiple small scale clearances can add up to affect the meteorological conditions at the regional scale.

Clearing forest reduces the above-ground biomass to about 2 per cent of its previous value.

A net uptake of carbon dioxide has been discovered for one tropical forest site. This raises the possibility that tropical forest may be a substantial sink in the global carbon balance.

An Amazonian deforestation modeling experiment, carried out with the land surface parameterization calibrated using ABRACOS data, predicted that a hotter climate, with less evaporation and reduced rainfall would follow deforestation.

It is worth explaining in greater detail the observed differences in transpiration and soil moisture giving their bearing on the distribution of biomes in Amazonia.

EVAPORATION

Rain falling on to vegetation is intercepted by the leaf canopy and some is evaporated back into the atmosphere without reaching the ground. Because forests are aerodynamically much rougher than grass, the turbulence over forest is stronger and water evaporated from the wet canopy of a forest can be easily moved away from the surface. This gives high evaporation rates from wet forest. The weaker turbulence over grass results in much lower evaporation rates. Measurements of interception loss at the ABRACOS forest sites at Marabá and Ji-Paraná show that 13% of the rain falling on the forest is evaporated in this way. The water vapor which is evaporated in this way is available for convective rainmaking storms, to give further rainfall downwind.

During ABRACOS the evaporation from the vegetation has been measured in a number of ways: from changes in soil moisture, by studying the water loss from individual leaves, or by measuring the water vapor moving through the turbulent boundary layer above the vegetation.

When there is no shortage of soil moisture the evaporation from the pasture and from the forest are quite similar between 3.5 and 5 mm/day. However during the dry season the two vegetation types respond very differently. Surface conductance of pasture falls as a result of stomatal closure and a reduction in leaf area. These processes act equally to reduce the surface conductance to about half of its value when the soil is moist. Thus evaporation is reduced to as low as 2 mm/day. In contrast, the conductance of the forest does not change noticeably during the dry season (evaporation between 3. and 4 mm/day), and the leaf area remains relatively constant throughout the year. For forest leaf area indices for both sites are just below six, i. e. 6 m2 of leaf per m2 of ground. In contrast leaf area index of pasture was found to vary between just over 1 at the Manaus site to a maximum of nearly 4 on the better soils near Ji-Paraná.

SOIL MOISTURE

Rainforest trees are often thought to have shallow root systems, with only a dense mat of roots near the soil surface. They do indeed have this dense mat of roots, but they are primarily for extracting nutrients. Rainforest trees also have deep roots, and the ABRACOS soil moisture measurements at all of the sites have shown that during dry periods the forest trees can, when necessary, use water from as deep as four meters below the surface and probably even deeper. The forest therefore has access to a large reserve of water which could last, if necessary, for several months. In contrast, grass in the pasture has much shallower roots and is only able to absorb water from the top 1 to 2 meters of soil. The amount of water available to the plants depends on the soil type as well as on the rooting depth, but once all the available water has been taken from this relatively shallow layer, the evaporation begins to fall and the grass begins to wilt and eventually to die. This is an important difference between them.

Measurements made in ABRACOS have shown that during rainy periods the proportion of the available energy at the surface which is used for evaporation is similar for forests and pasture. However, during periods of several days or weeks without rainfall, the evaporation from the pasture is reduced, whilst the forests continue to evaporate water at the same rate. During dry periods the pastures return less water to the atmosphere than the forests: this in turn reduces the likelihood of cloud formation and rainfall. In addition, less energy used for evaporation in the pasture means that there is more energy left to heat the air. Replacing the forests with pasture should therefore give hotter dry seasons with less rainfall. These changes will feed through the hydrological cycle and result in changes in river flow, but the severity of the impact will depend on the length of the dry season and on the soil type, which controls the water availability.

Taken together, there is a wealth of observational evidence that seems to suggest that the Amazonian rainforest is highly efficient in recycling precipitation water into the atmosphere.

DISCUSSION AND CONCLUSIONS

A question can be raised about the factors that determine the large scale biome distribution in tropical South America. Most of it is covered either by various forms of tropical forests or by savanna, except the dry high Andean Plateau and Northeast Brazil, covered by shrubs typical of semi-arid lands. To a large extent, the biome distribution can be accounted for by the climatic variables, primarily the rainfall distribution. For reasons pertaining to the general circulation of the atmosphere, the rainy season is short and yearly rainfall relatively small over the Andean Plateau and Northeast Brazil. That explains the vegetation types of those places.

This clear distinction becomes blurred upon analyzing the climatic differences between the savanna and forest biomes. For instance, annual rainfall is higher than 1,5 m in Central Brazil in the domain of the Cerrado. That is not significantly different from the annual rainfall of some parts of Amazonia, but covered by tropical forest. There is, however, a major difference in the climate of the areas covered by savanna and by forest: the length of the dry season. For savanna usually the dry season is well pronounced and much longer than for forests, even if the annual rainfall is not significantly different. Five to seven-month dry season for savanna, where rainfall can be almost absent in one or more months, as opposed to a dry season at most of four months, but with monthly rainfall larger than 40 mm in the driest month. To a first approximation, it can be said that the duration of the dry season is the major controlling variable for the geographical distribution of the biomes savanna and forest in tropical South America. In areas with short or non-existent dry season, forest is to be expected; in areas with a dry season longer than 5 months, savanna is to be found.

This simple biogeography model agrees remarkably well with the observed biome distribution in tropical South America east of the Andes. The transition between forest and savanna to the south, north and east of the Amazonian forest coincides rather well with the line separating areas with short dry seasons (forest) from the areas with longer dry seasons (savanna). Of course, such a crude model cannot explain the complexities of the ecotone where more than one biome co-exist under the same general climate.

To make matters more complex there are the intrusions of Cerrado into the forest, that is, in areas with short dry season such as the *campina* and *campinarana* vegetation of the Rio Negro basin. Conversely there are areas of riparian forest extending deep into the savanna. These can, however, be explained by considering that the important condition to assure the existence and maintenance of forests is a continuous supply of soil moisture to the roots throughout the year. The riparian forest roots thus access the water table throughout the year given its proximity to the river; the Cerrado intrusions, on the other hand, occur frequently on poorly drained plateauxs where there are severe soil moisture stresses during the dry season or on sandy soils with small water-holding capacity such as the *campina* and *campinarana*.

The ABRACOS results mentioned above showed a remarkable non-seasonality in forest evapotranspiration: 3.5 to 4.0 mm/day throughout the year for all experimental sites, including the sites in southeastern and southwestern Amazonia, where the dry season is more pronounced. On the other hand, the evapotranspiration of the grassy vegetation, which replaced the forest in the same regions, has shown marked seasonality with decreased evapotranspiration during the dry season. The longer the dry season, the stronger the reduction in evapotranspiration for the pastures. These observations lend credibility to the simple biogeography model described above in which the main factor is the ability of the forest rooting system to access soil moisture throughout the year.

It has been sometimes argued that an important factor in the biome distribution is soil type and soil nutrient content. It is possible that on smaller scales (hundreds of meters to tens of kilometers), these may play a determining role in establishing the vegetation type. However, on the large scale (hundreds of kilometers and larger), it appears that the most important factor is the ability of the soil to supply water to the forest roots throughout the year. This is directly linked to the length of the dry season. The savanna vegetation species are adapted to a long dry season. A related adaptation is fire-tolerance of these species. Fire is a common occurrence in the savanna and a vital factor in its ecology. On the other hand, the forest species are by and large not fire-tolerant. Given the high levels of moisture in the forest vegetation, it is an extremely unusual occurrence for a standing forest in Amazonia to catch fire.

REFERENCES

Bastable, H.G., Shuttleworth,W.J. Dallarosa, R.L.G., Fisch, G. and Nobre, C.A., (1993), Observations of climate, albedo and surface radiation over cleared and undisturbed Amazonian forest. Int. J. Climatology, **13:** 783-796.

Culf, A.D., Fisch, G. and Hodnett, M.G., (1994), The albedo of Amazonian forest and ranchland. Submitted to J Climate.

Dolman., A. J. and Gash, J.H.C., (1994), Tropical rainforests: hydrology and climate. In: Encyclopaedia of Agricultural Science, C.J.Arntzen (ed), Academic Press, Orlando. In press.

Fisch, G., Wright, I.R. and Bastable, H.G., (1994), Albedo of tropical grass: a case study of pre- and post-burning. Int. J. Climatology, **14:** 102-107.

Lucas, R.M., Honzak, M, Foody, G.M., Curran, P.J. and Corves, C., (1993), Characterizing tropical secondary forests using multi-temporal Landsat sensor imagery. Int. J. Remote Sensing, **14:** 3061-3067.

Manzi, A. O., (1993), Introduction d'un schéma des transfert sol-vegetation-atmosphere dans un modele de circulation generale et application à la deforestation Amazonienne. PhD Thesis, Université Paul Sabatier, Toulouse.

McWilliam, A.L.C., Roberts, J.M., Cabral, O.M.R., Leitao, M.V.B.R., de Costa, A.C.L. Maitelli, G.T. and Zamporoni, C.A.G.P., (1993), Leaf area index and above-ground biomass of terra firme rain forest and adjacent clearings in Amazonia. Functional Ecol., **7:** 310-317.

Nobre, C. A., Sellers, P. J., and Shukla, J., (1991), Amazonian deforestation and regional climate change. J. Climate, **4:** 957-987.

SHUTTLEWORTH, W.J. AND NOBRE, C.A., (1992), Wise forest management and its linkages to climate change. In: Wise Management of Tropical Forests, F.R.MILLER AND K. L. ADAM (eds), Oxford Forestry Institute, Oxford, p.77-90.

SHUTTLEWORTH, W.J., GASH, J.H.C., ROBERTS, J.M., NOBRE, C.A., MOLION, L.C.B. AND RIBEIRO, N.M.G., (1991), Post-deforestation Amazonian climate: Anglo-Brazilian research to improve prediction. *J. Hydrol.*, **129:** 71-86.

UBARANA, V.N., (1994), Experimentos observacionais e modelagem das perdas por interceptação o da precipitação o na floresta Amazônica. MSc Dissertation, INPE, São José dos Campos, Brazil.

WRIGHT, I.R., GASH, J.H.C., DA ROCHA, H.R., SHUTTLEWORTH, W.J., NOBRE, C.A., MAITELLI, G.T.M., ZAMPORONI, C.A.G.P. AND CARVALHO, P.R.A., (1992), Dry season micrometeorology of central Amazonian ranchland. Q.J.R. Meteorol. Soc., **118:** 1083-1099.

QUESTIONS

Question (1) – *Have you include the role of the Aluminum top soil?*

Nobre – No, because none of the stimulation have taken into account the Aluminum. Because basically they use, even when you stimulate to the climate over, let's say, ten years. The sea surface temperature that you impose in the stimulation are the climatological sea surface temperature. So they don't reproduce Aluminum. So the answer is no.

Question (2) – by prof. Othon Leonardos**:** *I think we have to make hypothesis in trying to find the tendencies towards the truth that made a very dangerous statement, which is very correct in the time spend that you are talking about. Tens of years... But when you increase a little bit of time spend, a statement concerning geology and soil chemistry has no importance to the biome distribution. It is a very dangerous one. I can't agree more with you that right now the vast majority of the Amazon forest is independent of rock and soil chemistry because the top soil has nothing. So the system is in self equilibrium; is maintained by the chemistry. But when you are talking about biome distribution, you cannot talk about time spend of just a few years, because you have to see the dynamic approach and this biome distribution is now there because of something that happened in the past.*

Have you mentioned about refuges and the tureen of this development from refuges? These refuges were distributed by the germophology which controls climate, and geology that controls the germophology and more than everything else by chemistry. And chemistry controls the chemistry of soil; and chemistry of rocks controls chemistry of forests. It is impossible to get a forest from nothing, just from climate itself.

Nobre – Yes. I said I was going to make a bulk statement, but, of course, I was expecting a reaction. I don't disagree with you except for one sentence: refuges. I think we are biologically determined by climate; not by germophology or geology. If you look at some famous specialists like prof. Vanzolini, and many others, the coincidence between where the refuges were found and the maximum rainfall is one to one. And I think this is easy to explain, because that is where you could sustain forest, with high rainfall, and then you add, why the rainfall was high in those areas of refuges? The answer is related to atmosphere and physics, and has nothing to do with geology or germophology.

Question (2) – *Maybe with topography?*

Nobre – Well, topography is not what we were talking about. Topography is a very important climate factor; climate determining factor. Absolutely, topography. In the Andes and also along the coast, the Atlantic coast, you have the conditions to have rainfall. Even during the last Ice Age maximum, you still have the conditions to have a relative maximum of rainfall along the coast, and also not far from the Andes. So I agree with you that over the long millions of years, what you said is correct. But the atmosphere has its own dynamics which is independent of geology, except of course the relief and the chemistry.

Question (2) – *We were tending to agree to our logic, but I think there is something wrong. When I say that there is a straight correlation of geology to forests, and you say: "No. It is a straight correlation from forest to climate only. I think the logic problem is that we are using linear logic; when a system is in a chain you have to ...*

a circle of logic. *Why you use this? You see, we are both correct and, more or less, we are saying the same thing. I will insist that you should see the Cerrado. The Cerrado flora distribution, the biologic distribution, is I would say, removing the gallery forest, which is partly controlled by geology, where the nutrients are as well as the humidity. But the thing is when you have the nutrients you can sustain a little bit of flora, and the flora self controls humidity and makes a microclimate. But it is controlled by the rock distribution, by chemical distribution, as well.*

Nobre – Yes. I think we could convert, but basically to an extent, I mentioned that the central argument I thought is soil moisturability. Of course, soil moisturability is controlled to a large extent by geomorphology. So in that sense, we agree.