Thematic week: Water and Land

Thematic axis: Land Use Planning, Forest Cover and Afforestation

Title of the presentation:

Effects of deforestation in the Amazon on the rainfall and evapotranspiration regimes

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Abstract:

In South America, Amazonia represent 7 million km^2, mostly constituted by dense tropical rain forest, thus representing a huge source of evapotranspiration and strongly affecting the regional rainfall regimes. In recent years, new findings of the LBA Project (now, the Research Program on the Biosphere-Atmosphere Interactions in Amazonia) have confirmed and explained better the role of the forest as a vital regulator of the regional water cycle, as well as of the whole South America. The forest emit a large amount of volatile organic compounds (VOCs) which contributes to produce shallow and relatively warm clouds, very efficient to induce rains in the region. Large scale deforestation can disrupt strongly this mechanism and deeply modify the processes of formation of clouds and rains, with reflections on other neighboring, or even far away regions. Amazonia functions as an important center for redistribution of the water vapor entering the basin from the Atlantic Ocean, thus partly regulating the annual distribution of rains in the central and southern regions of Brazil and even of South America. On the other hand, the large scale environmental and climatic changes affect the rainfall regime in Amazonia, as illustrated by the phenomenon El Niño, more frequent in the last years, and the strong Amazonian drought during 2005.

Key words: Forest ecosystem services; Climate change; Amazonian clouds and rains; Hydrologic cycle in Amazonia

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1. Introduction

Amazonia is a mega region of ca. 7 million km^2 in South America, mostly covered by dense tropical rain forest, and crossed by thousands of streams and rivers (Fig., 1) which constitute by far the largest hydrographic basin in the world, discharging into the Atlantic Ocean 210,000 $m^3 s^{-1}$ or 2.9 mm day^{-1}, which represents 18 % of all fresh water in the globe (Marengo, 2006). Average evapotranspiration in the Amazon basin is in the range of 3.5 – 4.0 mm day^{-1} while daily rainfall varies between 5.5 and 7.9 mm dia^{-1}. Mean annual rainfall is ca. 2300 mm, but several sub-regions within the Amazon basin present annual rainfall well above 3000 mm, as occur in west, northwest and north shore of Amazonia (Marengo, 2006).

Along the main channel (the Amazon River) and its tributaries, exist between 100,000 and 300,000 km^2 of periodically flooded areas (Junk, 1997), while the riverine zones of small streams can sum up to 1 million km^2. Recently, the importance of these areas for the regional carbon cycle was emphasized by Richey *et al.*, (2002). They estimated a CO_2 evasion of 1.2 ± 0.3 Mg C ha^{-1} yr^{-1} from rivers, lakes and flooding areas in central Amazonia, and an output of 0.5 $Gt.yr^{-1}$ from the basin. This carbon, likely generated by organic matter decomposition in the forest floor, is respired into rivers and riverine zones and then released into the atmosphere. Such coupled systems imply that changes in one can strongly affect the other.

Amazonia is located in the tropics, where energy changes between land surface and atmosphere are very intense. Due to its territorial extension and physical features, the region also is a huge source of evapotranspiration and strongly affects the regional and extra-regional rainfall regimes. Thus, changes in Amazonian ecosystems can have profound impacts on atmospheric circulation, moisture transport to the region and, consequently, to the hydrological cycle, not only of South America, but also of other regions in the world (Almeida *et al.*, 2007).

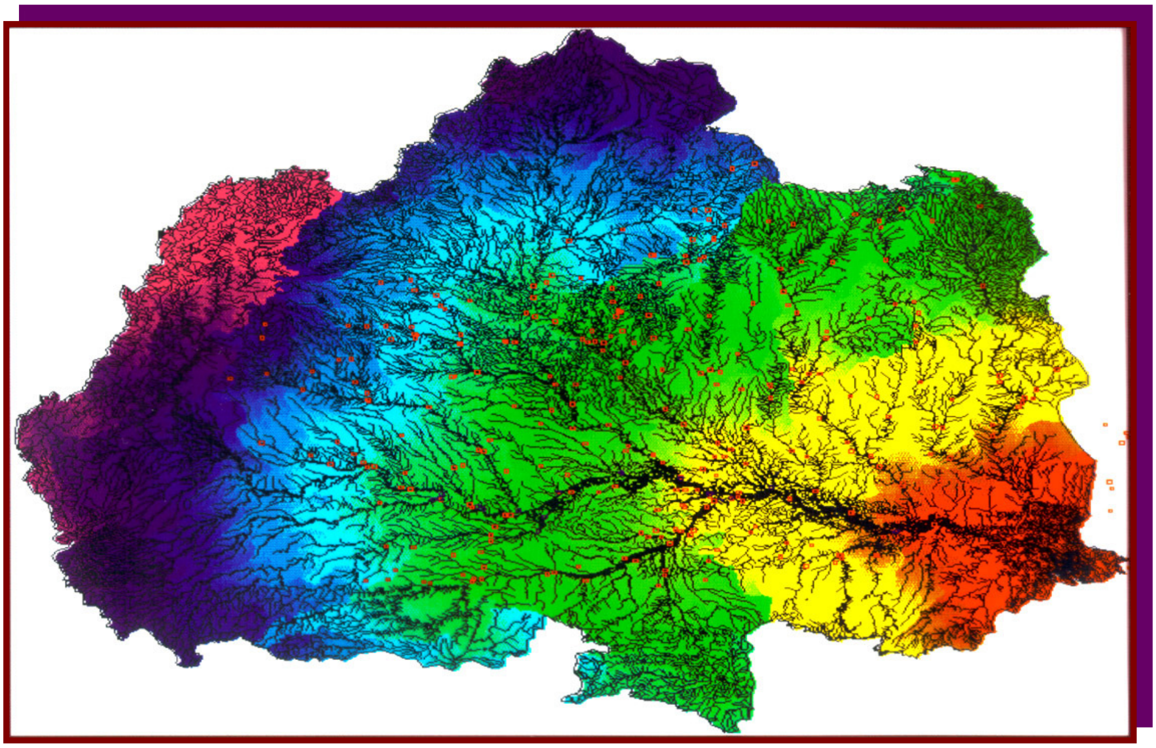


Figure 1: The Amazon River Basin: Colors represent time in months that the water takes to reach the ocean: red, 1 month; purple, 6 months.   (Courtesy: R. Victoria and J. Richey)

2. The forest-hydrological cycle coupling in Amazonia – insights from LBA Project

In recent years, new findings of the LBA Project (now, the Research Program on the Biosphere-Atmosphere Interactions in Amazonia, coordinated by MCT/INPA) have confirmed and explained better the role of the forest as a vital regulator of the regional water cycle, as well as of the whole South America.

Former studies report that half of the rainfall in Amazonia were originated from the local evapotranspiration (Salati & Vose, 1984), assuming that the whole evapotranspiration was transformed into rainfall in the region itself. However, studies taking into account the horizontal transportation of moisture associated to the regional evapotranspiration (e.g., Costa & Foley, 1999), estimated an annual recycling in the range of 20 – 35 %. During the rainy season, rainfall is generally is more than twice the evapotranspiration rate, implying that a greater portion of moisture needed for generate rains is imported from the Atlantic Ocean, mainly through the eastern winds (Marengo, 2006; Correia *et al.*, 2007). Although considerably lower than former estimates, this still represents a considerable part of the regional water balance: it is still true that an important part of Amazonian rainfall is fed by the evapotranspiration of its ecosystems, which represents 55-60 % of the precipitation. Since recycled water is a strong indicator of the climatic sensitivity related to changes in these processes, changes in vegetation cover due to deforestation which causes decrease in evapotranspiration will certainly affect the hydric balance of Amazonia and neighboring regions. Potential changes in this case are also related to other facts involved in the cloud and rain formation in Amazonia, as now explained by recent findings of LBA researchers, as well as by the role of Amazonia in importing and exporting water vapor.

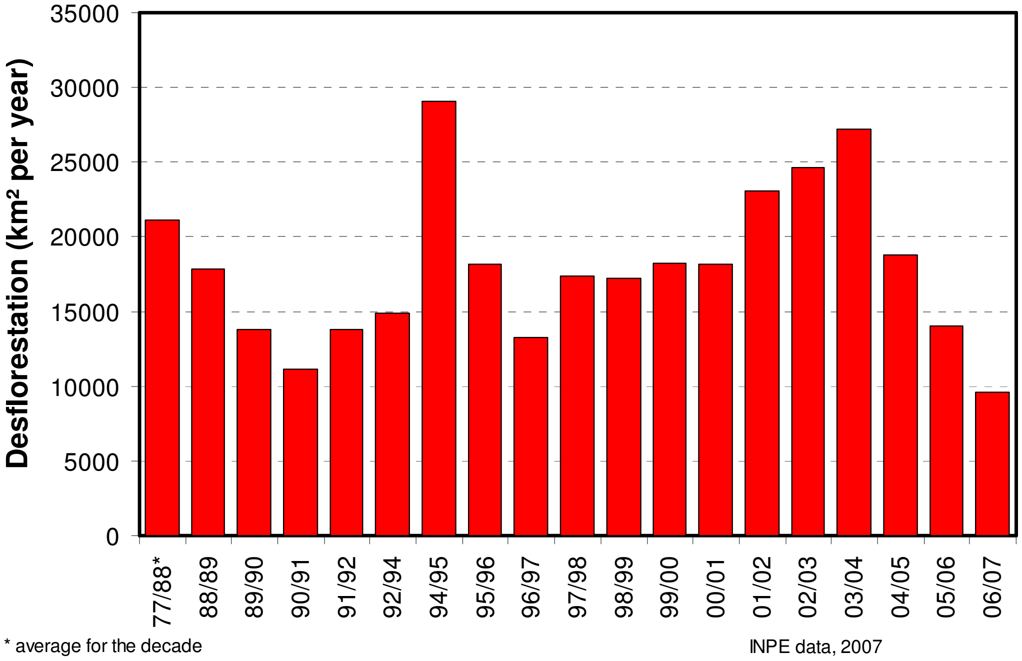
The aerosol particles, both natural and emitted by human activities, do exist everywhere in the globe, and affect climate in several ways: they act on the absorption and scattering of the solar radiation, on cloud formation, on ecosystem nutrient recycling, on the rainfall chemistry, on the visibility and health of people, among other important roles. However, the role of aerosol as cloud condensation nuclei (CCN) is absolutely critical for cloud formation and development; without aerosols, no clouds would exist, since it is compulsory to have a solid surface in order the water vapor can be condensed and produce raindrops.

In large patches of pristine forest in Amazonia, the concentration of particles in atmosphere is surprisingly low, comparable to those found in the remotest regions of the globe (Artaxo *et al.*, 2002). During the rainy season, only 200-400 particles cm^{-3} were found, ten times lower than observed in other continental areas, and from 100 to 1000 times lower than in burned areas in Amazonia, presenting concentrations as high as from 20,000 to 40,000 particles/cm^{-3}. The forest produce primary particles divided into two size classes: (i) the fine fraction (< 2 µm), constituted by the conversion to particles of biogenic gases emitted by the vegetation, such as isoprene and terpenes, together with some other volatile organic compounds (VOCs). The coarse fraction (> 2 µm) includes leaf fragments, pollen, fungi, bactéria, and a large variety of other biogenic particles.
In case the vegetation correspond to a forest, the major emissions of VOCs (with vapor pressure high enough to be vaporized and dispersed into the atmosphere) are of isoprene and terpenes. Once in the atmosphere, some VOCs are converted into aerosol particles through chemical reactions in presence of sunlight. Then, the particles play an essential role in the process of cloud formation, serving as cloud condensation nuclei (CCN), where the water vapor deposits to form raindrops. Clouds formed through this natural process are usually shallow, relatively warm, and very efficient in producing rains within a short time after beginning its formation, similar to what happens above the oceans. Because of that, these clouds have been called “warm clouds” and the forest producing clouds with oceanic characteristics named as “green ocean” (Artaxo *et al.*, 2002, 2005).

A second fact of primary importance for the regional and extra-regional climate, and specifically for the hydrological cycle, is the role of Amazonia in receiving and exporting water vapor from and to long distances. The annual water balance shows that Amazonia is a large importer of water vapor, especially from the Atlantic Ocean, which contributes with three quarters of the total moisture circulating in the region (Correia *et al.*, 2007). The other quarter is produced by evapotranspiration, while annual rainfall is twice that value. Thus, Amazonia exports moisture in an amount equivalent to twice the total regional rainfall or four times its evapotranspiration. Half of this is transported towards southern of South America, while the other half moves toward Pacific Ocean and Caribbean region. One can realize, then, that Amazonia stands as an important controller for the circulation of water vapor in the South American continent, affecting the distribution of rains in central and southern South America (Marengo, 2006). At the same time, it is possible to predict serious impacts on the present processes governing such movements of water vapor within and outside the Amazon basin.

3. Impacts of deforestation on Amazonian ecosystems and rainfall and evapotranspiration regimes

Amazonia has faced an accelerated process of deforestation in the last few decades. Only in Brazil, about 18 % of its Amazon forest has been converted into cattle ranch and agriculture (Fig., 2; INPE, 2007). The main process for land clearing and preparation is by slashing and burning the forest, mostly during the dry season, with several impacts, both direct and indirect, beneficial and damaging, at short or medium term.



* average for the decade

INPE data, 2007

Figure 2: Deforestation (in km² per year) in Brazilian Amazonia 1977-2007 (INPE, 2007).

In the last years, the deforestation effects on regional climate and hydrology have been evaluated through observational and modeling studies in Amazonia. The first observational studies (e.g., Gash *et al.*, 1996; ABRACOS Project) aimed to quantify the impacts of forest conversion to pastures on local microclimate (for instance, changes in air temperature, moisture, and evapotranspiration), and thus understand the processes of the biosphere-atmosphere interactions in the tropics. Experiments showed decreases in the absorption of solar radiation at the surface (because pastures reflect more radiation than the forests), and reduction in the evapotranspiration and air moisture in comparison to the forest, but failed to show conclusive results regarding changes in rainfall. An average 20 % decrease in evapotranspiration in pasture during the rainy season, and up to 40 % in the dry season over a 4 year period was observed in two LBA experimental sites located at Southest Amazonia (von Randow *et al*., 2004). The more accentuated reduction of evapotranspiration in pasture during the dry season is attributed to the shallower root system in comparison to the forest. Thus, available water for plant transpiration in pastures is much lower than in forests. Additionally, pastures have lower leaf density, thus decreasing the loss of water by interception (rain water retained in plant leaves and evaporated soon after rains).

On the other hand, climatic modeling has been used to evaluate the possible impacts of Amazonia deforestation on climate. The majority of these studies suggest annual reductions from 5 to 20 % in rainfall, from 20 to 30 % in the evapotranspiration, and increases from 1 to 4 ^{o}C in air temperature near the surface (Nobre *et al.*, 1991; Correia, 2006). However, changes in moisture convergence are still a controversial question in the different modeling exercises: while the majority of models show reductions in the moisture convergence, others present an increase (Almeida *et al*., 2007). The local circulation mechanisms very likely have an influence in the actual results of precipitation, since changes in rainfall are related to alterations in evapotranspiration, horizontal moisture convergence, and in atmospheric ascendant movements, all needed to produce clouds and rainfall.

Using the present scenario of deforestation (referred to the year 2003), a model showed that the increase in moisture convergence compensated for the effect of evapotranspiration reduction, leading to an increase in rainfall in the deforested area. Increases in cloud coverage and precipitation over deforested areas in middle of large extensions of forest in Amazonia have been observed by analyses of satellite data (Duriex, 2003) as well as by studies using regional numeric models (Avissar *et al*., 2002), suggesting a typical mechanism of local circulation. At deforested areas, the air close to the surface becomes warmer than the surrounding forest, carrying the colder and moister air of the forest towards the deforested area. Then, the moist air is elevated above the deforested area, producing clouds and, having enough moisture, may generate an increase in rainfall. Under other scenarios, despite generating an increase in moisture convergence, the reduction in evapotranspiration is stronger, leading to a deficit of precipitation in the deforested region, mainly in the dry season (Correia *et al*., 2007).

Trying to reconcile the outputs of different models, Avissar *et al*. (2002) report that deforestation up to a threshold of 20 or 40 % of the region would generate an increase in rainfall; above that level, a significant decrease in rainfall would take place in Amazonia (Fig., 3). Initially, deforestation effect can be the intensification of the horizontal gradients of temperature, inducing an increase in rainfall associated to local circulations. The rainfall increase could remain while there is an adequate supply of water vapor to keep rainfall, and deforestation is not reaching large areas.

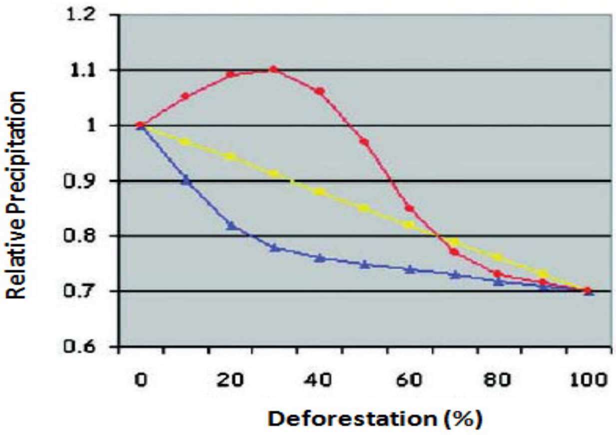


Figure 3: Modeling simulations on possible effects of deforestation on rainfall in Amazonia. The red line represents a LBA result, indicating that deforestation may increase rainfall while limited in area. After reaching a threshold, deforestation induces strong decrease in rainfall (Source: Avissar *et al.*, 2002 – LBA homepage).

In spite of a generalized lack of field measurements demonstrating the direct effect of deforestation on rainfall amounts or distribution, one study in Rondonia, southwestern Amazonia, presented the first direct evidences of rainfall decrease following deforestation. The results were amplified by the local topography, which presents higher elevations than in central Amazonia. The study was part of a LBA intensive field campaign of measurements, named WETAMC – "Wet Season Atmospheric Mesoscale Campaign", and made in connection with one of the field campaigns for validation of the TRMM (Tropical Rainfall Measurement Mission), called TRMM/LBA (Silva-Dias *et al.*, 2002). Results analysed were given by a S-Pol radar located at the central Rondonia, an Amazonian state characterized by strong rural development, mainly with pastures. The radar monitored continuously cloud formation and rains covering an axis of 180 km, with a 4-km resolution. Overall the results showed a decrease of 5 % in rainfall at the deforested region when compared to low-altitude forest areas, and a 20 % decrease in rainfall when compared to forests at higher altitudes (above 230 m asl) (Fig., 4).

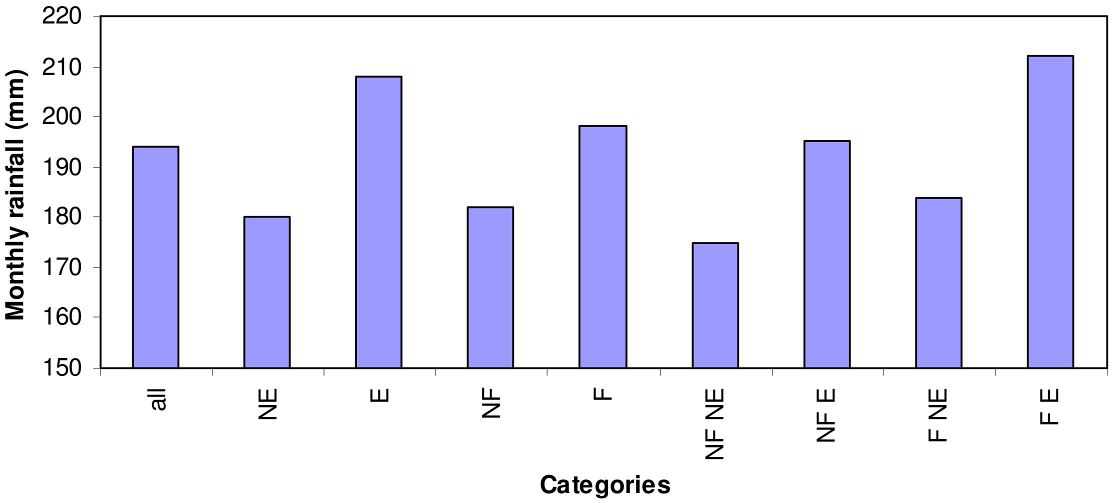


Figure 4: Monthly rainfall derived from S-Pol radar in Rondonia, for the following categories of vegetation cover and topographic situation: all altitudes; NE – non elevated; E – elevated; NF – non forest; F – forest. Elevation threshold was 230 m asl, and the vegetation cover used came from IGBP files with 1-km resolution. Adapted after Carey *et al.* (2001).

A direct impact of deforestation assessed by LBA research teams was that caused on former forest streams. Studies on the Ji-Paraná basin (Rondonia) showed that the spatial distribution of deforestation and soil properties resulted in different biogeochemical signals in streams and rivers of the region (Krusche *et al.*, 2005). Changes observed at the micro-scale constitute "biogeochemical signals" generated by the material processing at the riparian zones. As the rivers evolve to higher orders, the persistent signals in the fluvial channels are very closely related to the drainage basin characteristics (soils and land use), which, in turn, become the determinant of these systems dynamics. While at the macro-scale (the whole basin) the effects of land use changes are not yet detectable in Amazonia, the disruption of the structure and functioning is occurring at the micro- and meso-scales, with significant alterations in fluvial ecosystems.

Deforested streams showed much higher water temperature, concentrations of eroded nutrients and dissolved organic carbon, while dissolved oxygen was very low, indicating drastic changes in ecosystem functioning (creating an anaerobic system) and in the hydrology of the system. Higher CO_2 emissions and evaporation rates can be expected from such water bodies, but in some cases (especially when a grass cover grows on top of the stream) other kind of alterations may also be expected.

In a larger scale, deforestation may affect significantly the atmospheric processes, such as those of cloud and rainfall production over Amazonia. Using data from the tower network and field campaigns carried out by the LBA Program, it was possible to ascertain the changes in atmospheric chemistry following deforestation and biomass burning in different locations in Brazilian Amazonia. The studies made clear that the most important air pollution issue in South America is associated to the continental scale biomass burning during the dry season. Several hundred of thousands of fires each year promote huge changes in air quality and aerosol density and quality, causing: (i) severe health effects on the population; (ii) climate effects; (iii) weather effects. The large scale aerosol distribution over most of the (or even the entire) Amazonia, induce strong effects on the direct radiation balance and cloud formation, affecting the whole atmosphere thermodynamic structure. As a result, the atmosphere is stabilized, the available energy for surface processes is reduced, and precipitation may increase or decrease, depending on the scale deforestation (Artaxo *et al*., 2002). The kind of clouds produced in such altered environment is also distinct from that formed over pristine conditions in Amazonia (Artaxo *et al*., 2002; Andreae *et al*., 2004) mainly due to very distinct type and abundance of aerosol particles in the atmosphere.

In pristine conditions, during the wet season, when the natural emissions dominate, the concentration of particles generally varies from 10 a 15 $\mu g\ m^{-3}$, or from 100 to 300 particles cm^{-3}. In the dry season, because of burnings, concentrations increase to 300-600 $\mu g\ m^{-3}$, or 15,000–30,000 particles cm^{-3} (Yamasoe *et al*., 2000). The very high concentration of particles affects the balance of radiation, attenuating up to 70 % of the incident radiation, producing significant deficits of radiation at surface (Eck *et al*., 2003). At the same time, it has an important impact on the health of the population in Amazonia, causing a significant increase of respiratory diseases, among others.

In a polluted atmosphere, with a very high concentration of CCN, as during the burning season, the available water vapor is scattered among many particles, the raindrops grow slowly, and clouds continue to grow, and develop in depth. Many times, these clouds produce no rains, the raindrops evaporate and the water vapor is carried out to other regions. In case the raindrops reach more than 6 or 7 km of height, it may freeze and ice continues growing quickly while the clouds may grow up to 10-15 km of height, forming the Cumulonimbus type of cloud. The shallow clouds, typical of clean atmosphere, disappear and only rarely the deep clouds produce rains, together with many thunders and lightnings (Fig., 5; Andreae *et al.,* 2004). The deep clouds may be transported by strong winds at high altitudes for hundreds of kilometers away of its location of origin, exporting also the CCN within the original raindrops (Silva Dias *et al*., 2002). Such rainfall suppression can have important impacts on the functioning of Amazonian ecosystems (Artaxo *et al*., 2002).

Other important aspect of the cloud structure during the dry season, under strong impact of biomass burnings, is the significant presence of particles which able to absorb radiation, called “black carbon”, consisting of smoke particles from biomass burnings (Martins *et al*., 1998). Small raindrops in clouds with abundant smoke particles absorb radiation very efficiently, evaporating before being precipitated, thus intensifying the rainfall supression. As the concentrations of black carbon are usually high during the dry season (from 5 to 40 $\mu g\ m^{-3}$), this process is particularly important in Amazonia, compared to other regions in the globe.

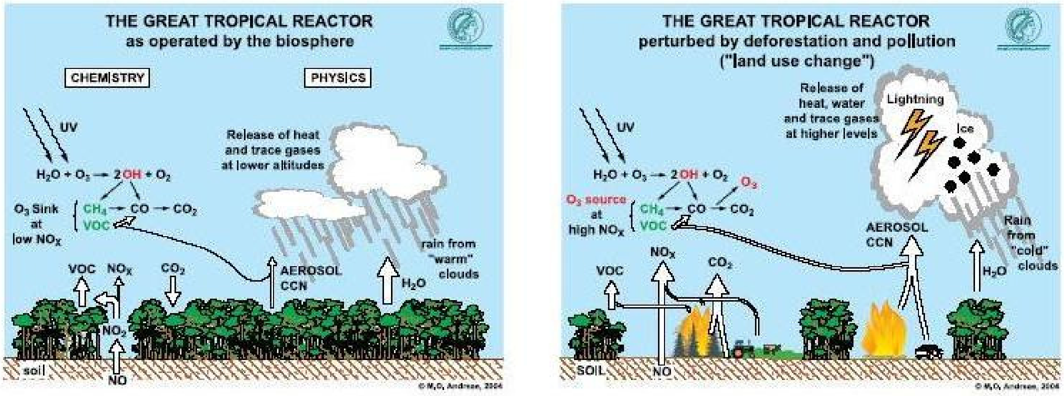


Figure 1: Biosphere-Atmosphere interactions in the Amazon: (a) in pristine conditions (b) as disturbed by deforestation and land use.

Figura 5: Main biosphere-interactions involved in cloud and rain formation in Amazonia: (a) over forests, in pristine conditions; (b) over large areas disturbed by deforestation and changes in land use (Source: Andreae *et al*., 2004; LBA homepage).

4. Implications of the new findings for resources conservation, sustainable development, and climate changes

The present type of dense tropical rain forest in Amazônia is sustained by the absence of a longer dry period, and an increase in the duration of the dry season can have important ecological consequences. Among other effects, a considerable increase of the forest susceptibility to fire events, especially at forest borders, would certainly occurs (Nepstad *et al*., 2001). That would produce a feedback process, with more fire events, less precipitation in dry periods, higher tree mortality, and, then, still higher forest susceptibility to fire. The final result could be the forest dieback, as predicted by some ecological models (Cox *et al*., 2004) and/or the gradual replacement of the dense and high-biomass forest by other vegetation types with low biomass and adapted to longer dry periods (Oyamma & Nobre, 200). In the last decades, several studies, including those of the LBA Program, are investigating signs of trends which could lead to these scenarios.

Natural climate variability occurs in response to changes in oceanic streams and in the inclination of the Earth’s rotation axis. In Amazonia, variations are observed at 10-20 years intervals, when successively the rainfall increases or decreases. When the phenomenon El Niño happens, rains are less abundant, especially in the north and east parts of the region. Stronger El Niño events, such as in 1997-1998 may cause heavy tree mortality in forest, and forest fires even at places usually free of fires. Experimental decrease in rainfall reaching the soil, simulating El Niño events during several years in sequence, was performed in Santarem, Para state, giving insights on the forest response. High tree mortality, lower soil and litter moisture, higher production of coarse wood debris, lower wood production, and other changes were observed (Brando *et al*. 2007), most of them contributing to a higher forest susceptibility to fire events.

Effects of deforestation in the Amazon on the rainfall and evapotranspiration regimes

In the year 2005, Amazonia suffered a very intense and unusual drought: it was not caused by events like El Niño, as with most previous droughts in the Amazon, but by the warming sea surface temperatures in the tropical North Atlantic Ocean (Marengo *et al.*, 2007). As a result of the drought, several major tributaries as well as parts of the main river itself contained only a fraction of their normal volumes of water, and lakes were drying up. The consequences for local people, animals and the forest itself likely were very serious. No mathematical model up to date is able to predict other similar events in Amazonia. Thus, the development of adaptation strategies for changed environments in Amazonia, caused by severe droughts needs to be seriously considered. That may include fire prevention in view of drier environments and increased forest susceptibility to fires, either natural or accidental.

In order to help preventing some of the hazards which may cause serious damages to the forest, the LBA Program and associated research projects in Brazil have noticeably increased the knowledge on the functioning of Amazonian ecosystems and, at the same time, developed some tools to be used aiming the conservation of natural resources and the sustainable development. Among these, the following contributions related to deforestation and hydrological cycle may be quoted:

- enlarged and upgraded observational network for hydrology and climatology;
- improved and robust remote-sensing techniques allowing accurate detection of deforestation, secondary succession and even understory forest damages, as well as structural and functional changes in the forest, allowing the adoption of techniques for detection of new deforestation areas, even those at limited scale, such as the clearings for selective logging or to build narrow illegal roads under the forest;
- the recognition of the vital role of the volatile organic compounds (VOCs), emitted by plants, in the production of clouds and raindrops;
- the understanding of the role of Amazonia on South American climate and pluvial regimes;
- the identification of the lasting and recurrent effects of selective logging and forest fragmentation on residual forests, which become increasingly susceptible to fire events;
- the recognition of a close coupling of land and water bodies regarding the carbon and water cycles at watersheds and basins;
- the evaluation of alternatives for reutilization or rehabilitation of abandoned or degraded lands through no-burning agriculture and agroforestry systems for producing food, fiber, and environmental services, including a recovered local hydrological cycle.

These contributions were instrumental to a better valuation of the forest ecosystem services: nutrient cycling, biodiversity, carbon, and water cycle. Especially the LBA data and calculations regarding the last two were vital to create the Amazonas state's program for climate change and environmental services. The program was just implemented, and is predicted to grow fast in the next few years, rewarding local communities for avoided deforestation and environmental services. Conservative practices like the rehabilitation of degraded areas through agroforestry or tree plantations, recovering soil properties and hydrology (also microclimate); forest conservation or tree plantations at stream/river forest edges to guarantee

They were also important for producing improved weather forecasts, allowing to include new LBA findings and knowledge of natural mechanisms into predictive models. The establishment of relationships between climatic factors and incidence of tropical diseases may help authorities to work out predictive models for public health prevention of malaria and other diseases.

It is true that present uncertainties for quantify the components of the hydrological balance of Amazonia, especially due to a deficient observational network, will remain on the account of global climate changes. Besides causing increases in temperature, climate changes will surely affect the atmospheric circulation and the rainfall regime of the Amazon basin. However, progresses were made and are expected to continue in the second phase of LBA Program, now starting, and through new initiatives at local, regional, and national level in Brazil and neighboring countries.

5. References

Almeida, C.; Vorosmarty, C.J.; Hurtt, G.C.; Marengo, J.A.; Dingman, S.L.; Keim, B.D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *International Journal of Climatology*, 27: 633-647.

Andreae, M.O.; Rosenfeld, D.; P. Artaxo, P.; Costa, A. A.; Frank, G. P.; Longo, K. M.; Silva Dias, M. A. F. (2004). Smoking rain clouds over the Amazon. *Science*, 303: 1342-1345.

Artaxo, P.; Gatti, L.V.; Cordova Leal, A.M.; Longo, K.L.; Freitas, S.R.; Lara, L.L..; Pauliquevis, T. M.; Procópio, A. S.; Rizzo, L.V. (2005). Química atmosférica na Amazônia: a floresta e as emissões de queimadas controlando a composição da atmosfera amazônica. *Acta Amazonica*, 35: 185-196.

Artaxo, P.; Martins, J.V.; Yamasoe, M. A.; Procópio, A. S.; Pauliquevis, T. M.; Andreae, M. O.; Guyon, P.; Gatti, L.V.; Cordova Leal, A.M. (2002). Physical and chemical properties of aerosols in the wet and dry season in Rondônia,Amazonia. *J. Geophys*. Res., 107 (D20): 49.1-49.14.

Avissar, R.; Silva Dias, P. L.; Silva Dias, M. A. F.; Nobre, C. (2002). The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA): Insights and future research needs. *J. Geophys*. Res. 107 (D20): 54.1-54.6.

Brando, P.M.; Nepstad, D.C.; Davidson, E.A.; Trumbore, S.E.; Ray, D.; Camargo, P. (2007). Drought effects on litterfall, wood production and belowground carbon cycling in an Amazon forest: results of a throughfall reduction experiment. *Phil. Trans. R. Soc. B,* doi:10.1098/rstb.2007.0031 Published online

Carey, L.D.; Cifelli, R.; Petersen, W.A.; Rutledge, S.A.; Silva-Dias, M.A.F. (2001). Characteristics of Amazonian rain measured during TRMM_LBA. *30th Conference on Radar Meteorology*, 12A, 9.

Correia, F. W. (2006). Impacto das modificações da cobertura vegetal no balanço de água na Amazônia: um estudo com modelo de circulação geral da atmosfera (MCGA). *Revista Brasileira de Meteorologia,* 21: 153-166.

Correia, F.W.S.; Manzi, A.O.; Cândido, L.A.; Santos, R.M.N.; Pauliquevis, T. (2007). Balanço de umidade na Amazônia e sua sensibilidade às mudanças na cobertura vegetal. *Ciência e Cultura,* 59: 39-43.

Costa, M.H.; Foley, J.A. (1999). Trends in the hydrologic cycle of the Amazon Basin. *J. Geophys. Res*., 104: 14189-14198.

Cox, P.M.; Betts, R.A.; Collins, M.; Harris, P.P.; Huntingford, C.; Jones, C.D. (2004). Amazonian forest dieback under climate-carbon cycle projections for the 21st century. *Theorethical and Applied Climatology*, 78: 137-156.

Durieux, L.; Machado, L.A.T.; Laurent, H. (2003). The impact of deforestation on cloud cover over the Amazon arc of deforestation. *Remote Sensing of Environment*, 86: 132-140.

Eck, T. F.; Holben, B. N.; Reid, J. S.; O'Neill, N. T.; Schafer, J.; Dubovik, O.; Smirnov, A.; Yamasoe, M.A.; Artaxo, P. (2003). High aerosol optical depth biomass burning events: a comparison of optical properties for different source regions. *Geophysical Research Letters*, 30(20): 2.035-2.048, doi: 10.1029/2003GL017861.

Gash, J.H.C.; Nobre, C.A.; Roberts, M.J.; Victoria, R.L.(1996). *Amazonian deforestation and Climate*. Wiley and Sons, New York, USA. 612pp.

INPE. (2007). PRODES. [Accesible: http://www.inpe.br/prodes] [Acceso: 09/06/2008]

Junk, W. J. (1997). General aspects of floodplain ecology with special reference to Amazonian floodplains. In: Junk, W. J. (ed.) *The Central Amazon Floodplain*. Springer-Verlag, Berlin. p. 3-20.

Krusche, A.V.; Ballester, M.V.R.; Victoria, R.L.; Bernardes, M.C.; Leite, N.K.; Hanada, L.; Victoria, D.C.; Toledo, A.M.; Ometto, J.P.; Moreira, M.Z.; Gomes, B.M.; Bolson, M.A.; Gouveia-Neto, S.; Bonelli, N.; Deegan, L.; Neill, C.; Thomas, S.; Aufdenkampe, A.K.; Richey, J.E. (2005). Efeitos das mudanças do uso da terra na biogeoquímica dos corpos d'água da bacia do rio Ji-Paraná, Rondônia. *Acta Amazonica*, 35: 197-205.

Marengo, J.A. (2006). On the hydrological cycle of the Amazon Basin: a historical review and current state-of-the-art. *Revista Brasileira de Meteorologia*, 21: 1-19.

Marengo, J.A.; Nobre, C.A.; Tomasella, J.; Cardoso, M.F.; Oyama, M.D. (2007). Hydro-climatic and ecological behaviour of the drought of Amazonia in 2005. *Phil. Trans. R. Soc. B* doi:10.1098/rstb.2007.0015 Published online

Martins, J.V.; Hobbs, P.V.; Weiss, R.E.; Artaxo, P. (1998). Sphericity and morphology of smoke particles from biomass burning in Brazil. J. Geophys. Res., 103(D24): 32,051-32,057.

Nepstad, D.; Carvalho, G.; Barros, A.C.; Alencar, A.; Capobianco, J.P.; Bishop, J.; Moutinho, P.; Lefebvre, P.; Silva, U.L.; Prins, E. (2001). Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management*, 154: 395-407.

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

Oyama, M.D.; Nobre, C.A. (2004). A simple potential vegetation model for coupling with the simple biosphere model (SIB). *Revista Brasileira de Meteorologia*, 19: 203-216.

Richey, J.E.; Melack, J.M.; Aufdenkampe, A.K.; Ballester, M.V.; Hess, L.L. (2002). Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO2. *Nature*, 416: 617-620.

Salati, E.; Vose, P.B. (1984). Amazon Basin: a system in equilibrium. *Science,* 225: 129-138.

Silva Dias, M. A. F.; Rutledge, S.; Kabat, P.; Silva Dias, P.L. ; Nobre, C.; Fisch, G.; Dolman, A.J; Zipser, E.; Garstang, M.; Manzi, A.; Fuentes, J. D.; Rocha, H.; Marengo, J;Plana-Fattori, A.; Sá, L.; Alvalá, R.; Andreae, M. O.; Artaxo, P.; Gielow, R.; Gatti, L. (2002). Clouds and rain processes in a biosphere atmosphere interaction context.*J. Geophys. Res.* 107 (D20): 39.1- 39.20.

von Randow, C. ; Manzi, A.O.; Kruijt, B.; Oliveira, P.J.; Zanchi, F.B. ; Silva, R.L.; Hodnett, M.G.; Gash, J.H.C.; Elbers, J.A.; Waterloo, M.J.; Cardoso, F.L.; Kabat, P. (2004). Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. *Theor. Appl. Climatol*. 1-22.

Yamasoe, M. A.; Artaxo, P.; Miguel, A. H.; Allen, A. G. (2000). Chemical composition of aerosol particles from direct emissions of biomass burning in the Amazon Basin: water soluble species and trace elements. *AtmosphericEnvironment*, 34: 1.641-1.653.