SUMMARY

THE ROLE OF FORESTS IN THE MAINTENANCE OF STREAM FLOW REGIMES AND GROUND WATER RESERVES:

A REVIEW OF THE SCIENTIFIC LITERATURE

MARIZA COSTA-CABRAL
SILVANA SUSKO MARCELINI

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The ***Land Use Initiative*** **(INPUT – Iniciativa para o Uso da Terra*)*** *is a dedicated team of specialists who work at the forefront of how to increase environmental protection and food production. INPUT engages stakeholders in Brazil's public and private sectors and maps the challenges for a better management of its natural resources. Research conducted under INPUT is generously supported by the Children's Investment Fund Foundation (CIFF) through a grant to the Climate Policy Initiative.* ***www.inputbrasil.org***

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SUMMARY

Prepared for:

Agroicone
Brazil

Prepared by:

Northwest Hydraulic Consultants Inc.
Seattle, Washington, USA

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Prepared by:

Mariza Costa-Cabral
Senior Scientist

Silvana Susko Marcelini
Senior Scientist

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EXECUTIVE SUMMARY

The role of forests in the maintenance of streamflow regimes and groundwater recharge is a complex one. Forests exhibit higher evapotranspiration rates compared to shorter vegetation, a difference that is largest in the dry season when the trees' deep roots can access ground water reserves not available to the shallower roots of other vegetation. The higher evapotranspiration from forests carries different implications, which can be conceptualized in simplified form as in Table 1. The table shows five different physical mechanisms by which forests influence local precipitation, streamflows, and groundwater storage. The signs (+ or –) specify which effects are positive and negative.

Table 1. Five major physical mechanisms by which forests' high evapotranspiration rates influence precipitation and hydrology. The direction of the effect, positive of negative, is indicated for each variable.

Mechanism:	***Effect on:***		
	Precipitation	**Streamflow**	**Groundwater Storage and Baseflow**
Influence on the atmosphere:			
I. Atmospheric moisture recycling	+	+	+
II. Local land-atmosphere interactions	+	+	+
III. Influence on large-scale atmospheric circulation	+	+	+
Influence on hydrologic pathways:			
IV. Reduced water yield		–	–
V. Increased soil permeability		–	+

The first three mechanisms in Table 1 pertain to the influence of high evapotranspiration rates on precipitation. Each of the three mechanisms has ample theoretical and observational support in the scientific literature, which we review in this document. Notably, however, the overwhelming majority of the scientific literature restricts itself to one or another of these mechanisms in isolation, usually without mentioning the others. This is a significant point because, in our assessment, these mechanisms act at different scales, and not considering all three results in partial and incomplete frameworks of analysis that are mutually disconnected and can lead to conflicting or paradoxical conclusions.

This "tunnel vision" focused on just one mechanism is all the more significant when we consider the topic of spatial scale. Mechanisms I, II, and III in Table 1 operate at different spatial scales. This is illustrated in Figure 1, which was published by Goessling and Reick (2011). Meteorologist Helge Goessling and Vegetation modeller Christian Reick, from the German Alfred Wegener Institute for Polar and Marine Research and the Max Planck Institute for Meteorology, respectively, are responsible for development of global climate models with state of the art mathematical representations of the interactions between vegetation and the atmosphere. In their 2011 manuscript, they explain that to analyze and understand how evapotranspiration influences precipitation, it is necessary to consider mechanisms I, II and III together, and to recognize that they operate at different spatial scales. Mechanism II, local coupling, can also result in an intensification of precipitation over deforested areas located downwind from forested areas, because the more intense surface heating over those cleared areas (without the cooling effect of transpiration) can promote convection of the moist air that arrives from the nearby forest. This phenomenon has been observed in the Amazon region and can be erroneously interpreted as if the further clearing of forest would further increase rainfall. It would not, because it is the remaining forest which, through mechanisms I and III, provides the moist air.

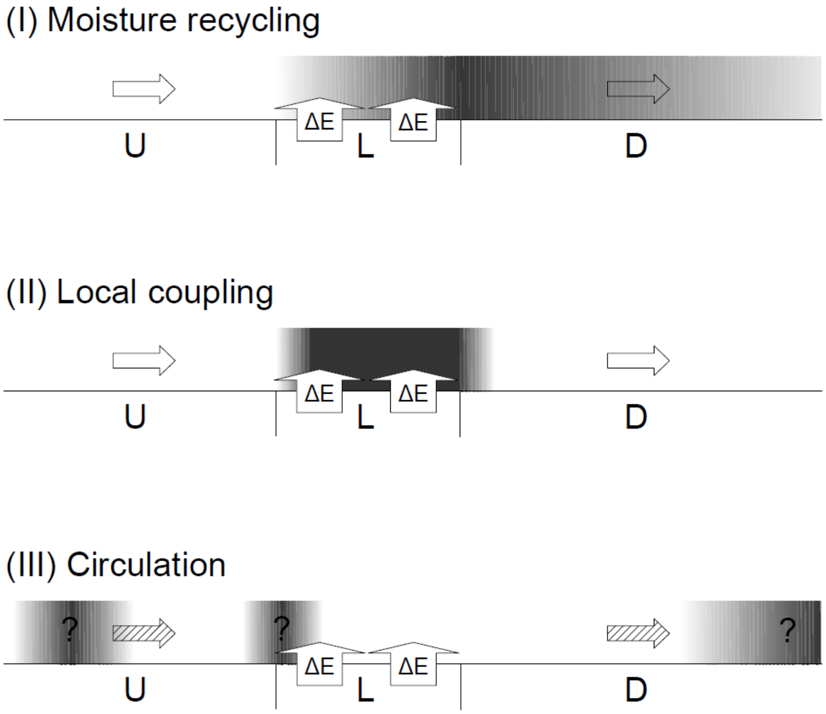


Figure 1. **Schematic of three mechanisms via which evaporation affects precipitation. The effect of each mechanism is shown isolated from the others. The arrows pointing to the right indicate the wind direction. The color gradients indicate the regions where precipitation responds (either positively or negatively). U= upwind region, L = local region, D= downwind region, ΔE = imposed evaporation anomaly. (I) Moisture recycling: The precipitation response, caused by changes to the atmospheric moisture budget, grows gradually over the region of the imposed evaporation anomaly, then decays (slowly) over the downwind region. (II) Local coupling: The precipitation response, caused by changes**

to the thermal structure of the atmosphere, collocates with the imposed evaporation anomaly. A slight downwind shift is indicated because the structural change may need some time to develop. (III) Circulation: The precipitation response may occur anywhere, caused by changes to the 3-D large-scale atmospheric circulation (indicated by the hatching of the wind-arrows). While mechanism (I) accounts for the effect of ΔE on the vertically integrated atmospheric moisture budget, mechanisms (II) and (III) account for modified energetics that come along with ΔE (in particular changes in temperature). This figure and caption are reproduced from Goessling and Reick (2011).

Mechanism I is moisture recycling. The atmospheric moisture lost to precipitation is replenished by the high evapotranspiration rates from forests, so that the moisture decline with distance inland from the ocean is very gradual. Regions located downwind from forests benefit greatly from the arrival of this moist air, despite the geographical distance to the coast. Moisture recycling has long been recognized as a major component of the Amazon River basin's hydrology, since the isotope studies by Salati et al. (1979). The latest piece of evidence came from Spracklen et al. (2012) who combined satellite observations of rainfall over the Amazon with modeled air trajectories, to show that those trajectories passing over forests produce more than twice as much precipitation as those who pass over non-forested areas (although Makarieva et al., 2014, pointed out that Spracklen's results may also reflect mechanism III). The recent study by Jasechko et al. (2013) showed that most of the evapotranspiration flux worldwide is composed of transpiration, with evaporation representing a smaller fraction, placing forests in a water cycle leading role.

Mechanism II is local coupling. High evapotranspiration transfers latent heat to the atmosphere, which changes the thermal structure of the atmospheric column directly above, promoting precipitation. Other factors are generally at play, such as the organic substances emitted by the forests' canopy which promote condensation. The effects on precipitation are localized. A slight shift in the downwind direction may occur because the atmospheric changes may take some time to develop.

Mechanism III influences the large-scale circulation of the atmosphere. As a result from this mechanism, precipitation changes result anywhere, including remote regions of the world – a type of phenomenon termed "teleconnection" – although in this document we focus on its effects on precipitation over South America. Goessling and Reick (2011) used a global climate model to conduct an extreme experiment where all continental evapotranspiration was eliminated worldwide. The modeled atmospheric circulation showed major changes in the global Hadley circulation and associated changes in the strength and position of the inter-tropical convergence zone (ITCZ) – a key influence on South American precipitation. They report large simulated declines in precipitation over most of South America, and they emphasize that mechanism I (moisture recycling) is not sufficient to explain these results, which illustrate the importance of mechanism III. Contributions from mechanism II (local coupling) are also important.

That changes in evapotranspiration in tropical forested regions are capable of altering large-scale atmospheric circulation patterns and intensity, thereby causing changes in precipitation, has been recognized at least since the 1958 manuscript by Riehl and Malkus. These authors characterized tropical

South America as a major center of convective activity (mostly developed within large cumulonimbus clouds) that continuously releases heat into the atmosphere, thereby influencing the Hadley-Walker circulation and the global circulation. The Hadley-Walker circulation represents the global conveyor belt that redistributes water and energy from the tropics to the subtropics.

Several modeling studies have confirmed this effect on the Hadley-Walker circulation. For example, Kleidon and Heimann (2000) performed global climate model experiments in which they changed the land cover over tropical South America. They found that the forested land cover, due to its higher evapotranspiration rates, results in a strengthening of the Hadley-Walker circulation to the benefit of rainfall over the forest. The difference in evapotranspiration rates between forests and shorter vegetation cover is especially large during the dry season, because the trees' deeper roots are able to access groundwater reserves that are not accessible to shorter vegetation.

Kleidon and Heimann (2000) conclude that "*deep rooted vegetation is an important part of the tropical climate system*" and, based on their global climate model simulations, they report that "*Without the consideration of deep roots, the present-day surface climate cannot adequately be simulated*." These authors pointed to deficiencies in the global climate models of their time where land surface parametrizations generally used rooting depths of less than 2 meters, in contrast to some observations reports roughly ten times greater. The higher evapotranspiration rates from forest versus shorter vegetation cover at different locations in Brazil were documented in LBA's flux tower experiments, which we include in this review.

Like Kleidon and Heimann's (2000) model and the up to date Goessling and Rieck (2011) model, global climate models in general are encoded with physical-mathematical formulations of land surface-atmosphere interactions where the heating effect of intense evapotranspiration on the atmosphere influences large-scale atmospheric circulation. Thereby, mechanism III is embedded in climate simulations and future climate projections, without representing any type of contentious issue. Mechanism III simply arises as a large scale effect of well known thermodynamic phenomena at the land surface-atmosphere interface.

More recently, it was proposed that in addition to these thermodynamic phenomena, there is an additional phenomenon that has so far been neglected and, when included, further strengthens mechanism III considerably. The proposition is that the loss of mass from the atmosphere during the process of condensation results in a significant drop in air pressure which, if explicitly incorporated in climate models, has important effects. The general physical phenomenon that is being referred to has long been recognized, however, the mathematical formulation of its strength is surprisingly difficult and contentious. The proponents of the far-reaching formulation, known as the "biotic pump" theory, are Anastassia Makarieva and Victor Gorshkov, researchers of the Theoretical Physics division of Russia's Petersburg Nuclear Physics Institute, who frequently collaborate with Brazilian researchers and have led a series of intriguing manuscripts published in the last decade.

In our review of the scientific literature, we found numerous instances of misunderstanding, where the manuscripts appear to equate mechanism III with the biotic pump theory only, not realizing that the biotic pump theory is only one of the possible contributing explanations for mechanism III, which predates this particular theory by several decades. This confusion is significant because the biotic pump theory remains contentious, with important aspects of its mathematical formulation having been challenged by Meesters et al. (2009), receiving a response in Makarieva and Gorshkov (2009b), and there not appearing to be a widespread agreement about it in the scientific community. Theoretical scrutiny of the theory is made difficulty in part because the highly advanced formulation makes it difficult to follow for many researchers.

The confusion is also significant because, when it is (wrongly) believed that the biotic pump theory being the only explanation for mechanism III, there is a risk that any evidence supporting mechanism III will be interpreted as confirmation for the biotic pump theory. The biotic pump theory has compared favorably to observations, but in our view it has not been shown in the scientific literature reviewed that previous physical-mathematical formulations of mechanism III are not also in agreement to observations. For example, Poveda et al. (2014) state they are performing testing the biotic pump theory, and Nobre (2014) states that Poveda et al. (2014) has provided observational confirmation of the biotic pump theory. However, in a more detailed reading of Poveda et al. (2014) we find the possibility is left open that the more traditional physical basis for mechanism III may suffice to explain the results. They write (p. 99): *"It could be explained by (1) surface convergence favored by the release of latent heat in the region's extraordinarily intense storms and mesoscale convective systems and (2) atmospheric pressure gradients created by the condensation of water vapor evapotranspired by the tropical rainforest (…)"* Explanation (1) refers to the traditional physical basis for mechanism III, while explanation (2) is the biotic pump theory.

In the biotic pump theory, forests attract moist air masses toward themselves by increasing their own evapotranspiration rates, which leads to air saturation and condensation with a concomitant drop in air pressure. The lowered air pressure pulls in new, moist air masses – thus acting as a biotic pump for oceanic moisture that provides a positive feedback to precipitation. Air saturation is achieved with even small increases in evapotranspiration rates because the air above tropical forests is kept close enough to saturation as a result of moisture recycling (our mechanism I) and circulation (mechanism III itself). The biotic pump theory as formulated by Makarieva and Gorshkov yields more powerful horizontal atmospheric pressure gradients than previous formulations, which were based on heat transfer from land surface to atmosphere.

All formulations of the forces driving mechanism III – either the more traditional formulations based on the atmosphere's thermal gradients, or those unrelated to the biotic pump theory as formulated by Makarieva and Gorshkov – have very great consequences for science and policy at a global scale. Because of this mechanism's importance, it is deserving of intense further research leading to the scrutiny of its theoretical components, and rigorous testing using observational evidence, with the goal of establishing a resilient theory. One of the consequences of mechanism III, with particularly major consequences to forest policy worldwide, is that the high evapotranspiration rates associated with a densely forested region bring in humid air masses and, therefore, the elimination of these forests would lead to much drier conditions – which, eventually, would preclude future forest regrowth, originating a stable new dry climate.

Some researchers have suggested that the topical forests' high evapotranspiration throughout the dry season is an indication that it is resilient to droughts. In this literature review, we found such evidence to be lacking. To the contrary, the Amazon's forests suffered considerable losses during the severe droughts of 2005 and 2010. In 2005, researchers reported large losses in biomass in the areas affected (due only in part to thunderstorms and wild fires). Such losses were consistent with the results from the deliberate drought experiments where rainfall was consistently siphoned off from test plots of forest (e.g., Costa et al., 2010). The 2010 drought was spatially more widespread, affecting over half of the Amazon's area, and resulting in the lowest streamflow ever recorded at Manaus.

It is hypothesized by many researchers that the 2005 and 2010 droughts were not isolated incidents, but the culmination of generally drier conditions observed from about 1970 to present. Wang et al. (2011) suggested that vegetation dynamics gives rise to persistence of precipitation anomalies across multi-year periods. This is possible due to the strong coupling between soil moisture and precipitation, mediated by the forests – as demonstrated in Wang et al.'s (2011) modeling experiments, reviewed in section 2.6. Saatchi et al. (2013) documented the persistence of canopy damage after the 2005 drought.

Wang et al. (2011) conclude as follows, ending in an important admonition: *"Due to the damping effects of vegetation, the several years following a severe drought in a region may be more prone to recurrent droughts, making it more likely for drought years to occur as a cluster. A similar statement holds for flood years. In the Amazon region, the past decade witnessed two extreme droughts, one in 2005 and a much more severe one in 2010 that coincided with the local dry season [e.g., Marengo et al., 2008, 2011; Lewis et al., 2011; Xu et al., 2011]. The drought in 2010, a "once-in-a-century" event, caused substantial reduction of vegetation greenness across the Amazon basin south of the equator that did not recover when the rainy season precipitation returned to normal [Xu et al., 2011]. Results from our study suggests that, in absence of extremely strong oceanic forcing favoring precipitation in this region, many areas of Amazon will be prone to recurrent droughts in the several years following the 2010 drought."*

Having shown us how major canopy damage (caused by the 2005 drought) can lead to increased likelihood of future droughts, the years 2005 and 2010 brought home the message of just how important the forests are maintaining dry season precipitation rates throughout northern and central South America.

Given the multiple benefits of forests, including in maintaining precipitation through vast regions of South America, there are good reasons to take advantage of degraded areas to promote afforestation (or reforestation). What localized effects might we expect following the afforestation of a degraded are? The structure and permeability of the soil will recover gradually due to the beneficial effect of root development, as well as gradual increase in the thickness and quality of the soil, particularly humic complexes which are formed in the layer of fallen leaves in soil. The increased permeability contributes to decrease runoff and increase soil moisture and groundwater recharge. Humic complex also contribute to the retention of soil moisture.

The reforestation of degraded areas will introduce a tendency to greater water loss through evapotranspiration (mechanism IV), but on the other, a tendency to lower losses by lateral flow quickly to the surface or shallow (mechanism V). The effect on the availability of local water will depend on the balance these two opposing tendencies. And this balance depends on the specific local factors of climate, soil, topography and specific location of the reforested area.

In some places where water resources are limited, reforestation in riparian areas compared to reforestation in places further upslope and further away from the rivers, resulting in greater losses by evapotranspiration due to higher average soil moisture and shallower groundwater tables. Forest plantations along the edge of agricultural fields can sometimes use groundwater resources that are in excess and are not accessible to the shallow roots of crops, and can capture runoff of these plantations and lead to infiltration of this flow, reducing the risk of local flooding and over-saturation of the soil in the wet season. The perimeter ratio of the area of reforested area and its alignment relative to the slope elevation contours are also factors that affect groundwater consumption. In areas influenced by winds with certain orientation, the forested edges are capable of capturing rain falling diagonally and thus increase the rain catchment within the property.

In many cases, afforestation leads to a reduction of base flow. In areas that were originally forested, the base flow may therefore turn out to be closer to the original historic flows. In areas served by dams, the effects of reforestation of degraded areas on local water resources should be very small or negligible because of the possibility of using dam releases to enhance base flows.

Through mechanisms I, II, and III, the forests bring and maintain moisture over vast regions of South America (section 2), and their dominant effects on surface and subsurface runoff are overwhelmingly positive. This is a principal finding of our literature research. Through mechanism IV, localized effects of afforestation will in most cases lower surface and subsurface runoff (section 3), although management strategies are available to minimize local effects (section 3.2). Through mechanism V, localized effects of afforestation may enhance sub-surface flow through the improvement of soil infiltrability and drainage, although many years, up to a few decades, may be required to achieve significant soil changes. This is especially likely to occur in previously degraded areas.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Important research studies published the last few years have greatly improved our understanding of the role of tropical forests in the hydrologic cycle and the maintenance of seasonal streamflows and groundwater reserves throughout Brazil. These studies include different and independent methodological approaches, increasing our confidence in the picture that emerges from these multiple sources. Here we review major recent studies and summarize the state of current understanding of the effects of land cover on seasonal rainfall, stream flows and groundwater reserves, and how those effects vary across spatial scales.

2 HOW DO CHANGES IN LAND COVER AFFECT RAINFALL?

2.1 Introduction: Atmospheric moisture fluxes

The answer to the question *'How do changes in land cover affect rainfall?'* is a complex one. We often encounter answers focused entirely on the phenomenon of moisture recycling over different land cover types. Recycling is of major importance, yet is far from the only avenue by which changes in evapotranspiration can affect rainfall. Here we review the evidence presented in the scientific literature for the presence of three major physical mechanisms through which evapotranspiration can affect rainfall: moisture recycling, local surface-atmosphere coupling, and atmospheric circulation. These three mechanisms, reviewed in section 2.2 through 2.5, act on different spatial scales and sometimes influence rainfall in opposite directions. Consideration of all three mechanisms and how the balance of their effects often plays out differently at different spatial scales is crucial to our interpretation of observational datasets and model simulation results, and to our understanding of the hydrologic impacts of land cover change across scales.

Before we proceed to analyze the three mechanisms, we provide in this section an overview of the atmospheric moisture sources and fluxes over South America and Brazil in particular. We mention some of the observational evidence for the central role played by forests, in particular the Amazon forests, in providing precipitation over subtropical Brazilian regions during the dry season. Different types of additional evidence are mentioned or reviewed throughout this document.

Given the central role of evapotranspiration throughout this document, we also provide in this section a succinct summary of the evapotranspiration observations from the Large-Scale Biosphere-Atmosphere Experiment in Amazônia (LBA) project.

2.1.1 Overview of the atmospheric moisture sources and fluxes over Brazil

The oceans represent the major source of moisture for continental precipitation, and the Atlantic Ocean is the dominant source of moisture for northern and central South America (Figure 2). Moist air masses from the Atlantic Ocean are brought to the continent by the westerly winds, a feature of the Hadley-

Walker circulation. The Hadley-Walker circulation represents the global conveyor belt that redistributes water and energy from the tropics to the subtropics. As reviewed in the sections that follow, there is observational evidence and theoretical hypotheses (under mechanism III) for a major role of forest evapotranspiration in strengthening the Hadley-Walker circulation so as to favor the transport of moisture towards themselves, in the process bringing moisture to much of the South American continent.

After entering into northern tropical South America and being transported over the Amazon River basin, atmospheric vapor is regularly replenished in part by local evapotranspiration, in a process termed "moisture recycling" or "precipitation recycling". Moisture recycling (mechanism I) has long been recognized as a major component of the Amazon River basin's hydrology (Salati et al., 1979; Eltahir and Bras, 1996; Trenberth, 1999; Dirmeyer and Brubaker, 2007; van der Ent et al., 2010; Goessling and Reick, 2011; Spracklen et al., 2012). Most of the evapotranspiration flux is composed of transpiration, while evaporation represents a smaller fraction (Jasechko et al., 2013).

The special similarity between clouds observed over ocean surfaces and over the Amazon forest was such that Williams et al. (2002) termed the Amazon a "green ocean". There is however a major difference between the clouds above the ocean and those above the Amazon's "green ocean", and that is the much higher rainfall over the latter year round. This is explained in part by mechanism II, local coupling. There is however evidence that the dry season may be growing drier in the Amazon region (Marengo et al., 2011). The Amazon recently experienced two major ("historical") droughts spaced just 5 years apart, in 2005 and 2010. In section 2.5 we explore interpretations that have been suggested in recent literature.

Poveda et al. (2014) provides a succinct, clear description of moisture transport and fluxes over South America, which we quote next. See also our conceptual Figure 3, and the observations-based aerial rivers in Figure 4, reproduced from Poveda et al. (2014).

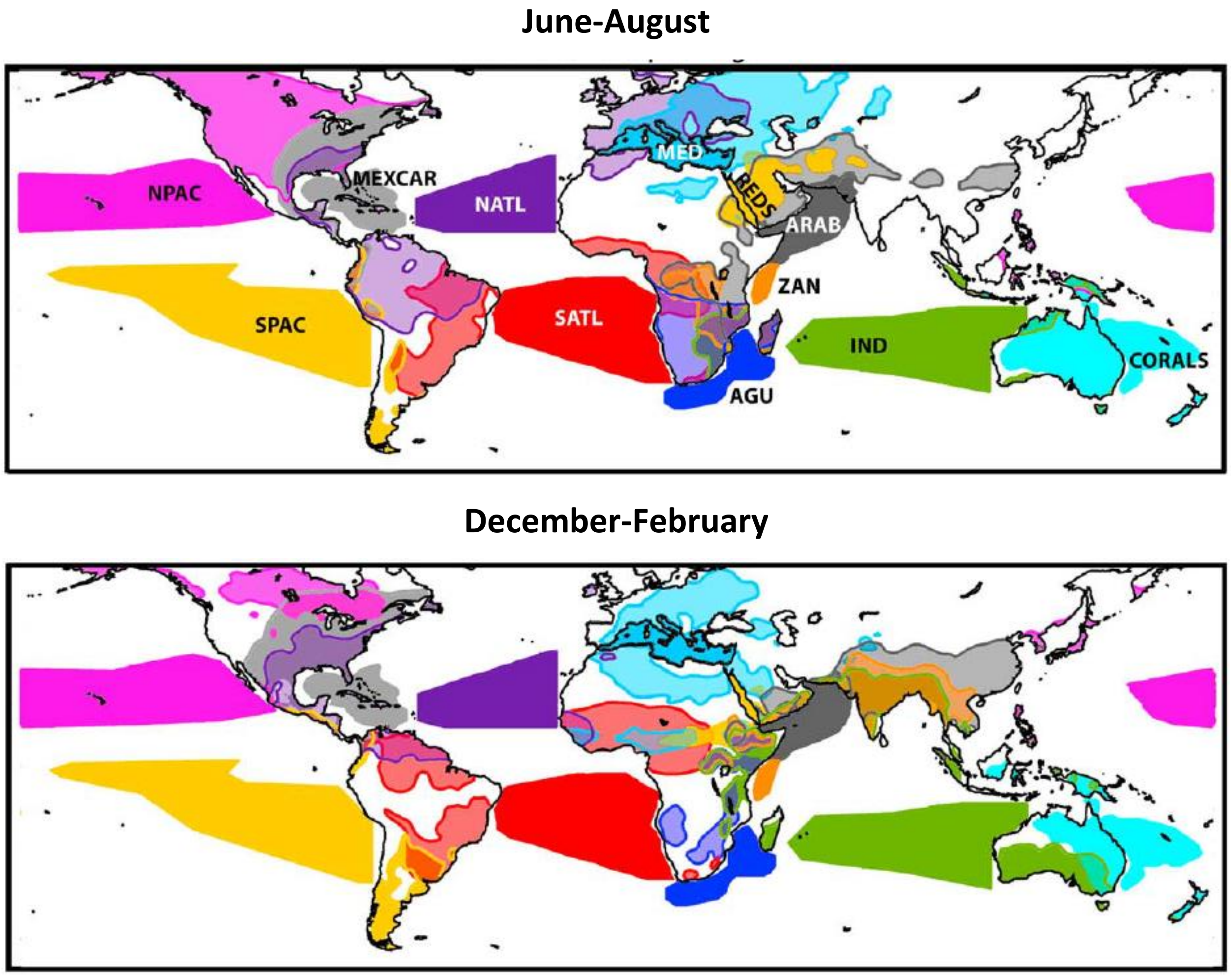
> *"The transport of moisture through north-eastern South America is associated with the dynamics of the easterly trade winds from the Atlantic Ocean all the way to the Andes, where they veer to the southeast to reach the La Plata River basin [Byerle and Peagle, 2002]. The flow develops a core of particularly high speed, so-called South American low-level jet (SALLJET) [Marengo et al., 2004; Grimm and Tedeschi, 2009]. Such flow of moisture east of the Andes was identified as an atmospheric river [Newell et al., 1992], in reference to filamentary structures in the vertically integrated moisture flow field. The work of Moraes-Arraut et al. [2012] broadened this concept to that of aerial rivers (AR, hereafter), defined as preferential filamentary or broad pathways of moisture flow, because of their near-complete symmetry/analogy with surface rivers, which upon slowing down and broadening spatially form atmospheric lakes containing the highest amount of precipitable water, analogous to depth in surface lakes.*

> *"Contrary to surface rivers, AR acquire water from evapotranspiration and lose it by precipitation (equation (2)). The studies of Arraut and Satyamurty [2009] and Moraes-Arraut et al. [2012] investigated the seasonal dynamics of AR over Amazonia and subtropical South America, and confirmed that both the trade wind flow from the Atlantic Ocean into Amazonia, and the north/northwesterly flow to the subtropics, east of the Andes, satisfy the aforementioned AR criteria. The AR east of the Andes is active year-round, although the highest amounts of moisture transport occur during the austral summer, associated with more intense trade winds from the North tropical Atlantic, but also with water vapor evapotranspired in Amazonia. The long-term mean discharge of the AR east of the Andes to the subtropics during dry seasons varies between 10 and 23 Gt d^{-1} (115,000–267,000 m^3 s^{-1}), for which the zonal airflow coming from the Atlantic, as well as local net soil evaporation constitute nearly equally important contributors [Moraes-Arraut et al., 2012]."*

The observed regional moisture gradients resulting from this pattern of moisture transport, and land surface-atmosphere interactions, are depicted in Figure 5. Arraut et al. (2012) presented a diagnosis of seasonal patterns of atmospheric moisture transport, based on the gridded observations-based dataset known as ERA-Interim (European Centre for Medium-Range Weather Forecasts Interim Reanalysis; Dee et al., 2011). In their study, they found it useful to define the concepts of "aerial river" and "aerial lake," atmospheric analogs of surface rivers and lakes. They describe how the trade winds entering the Amazon River basin form an aerial river, which is deflected by the Andes mountain range and moves towards the southeast and south. This flow is particularly marked in the wet season, i.e., November through March (Figure 4). Aerial lakes are the sections of a moisture pathway where moisture flow slows down and the flux broadens and deepens, forming an atmospheric reservoir of moisture. In the wet season (November through March), moisture from the large aerial lake of the southwestern Amazon is transported mostly southward to subtropical latitudes.

In the dry season (July-August), flow of moisture from the southwestern Amazon aerial lake is mostly to the northwest toward Central America. Nevertheless, the southern Amazon region is an important source of atmospheric moisture for southern South America during the dry season (Arraut et al., 2012; Poveda et al., 2014). Thus, Arraut et al. (2012) write that *"Subtropical rainfall is partly fed by rain farther north earlier in the year."* Arraut et al. (2012) emphasize that this dry season moisture source is possible only because of the Amazon forest's high dry season evapotranspiration rates, and they add, *"For this reason, it is possible that the moisture source behavior would not persist in a deforestation scenario."*

The observations-based study of Arraut et al. (2012) found that *"Discharge of the aerial river east of the Andes to the subtropics during the dry seasons varied between 10 and 23 Gt day^{-1}, comparable to the Amazon River discharge. The two most important contributions were flow from Amazonia and zonal [east to west] flow coming from the Atlantic."*


June-August

December-February

Figure 2. Schematic representation of moisture source and continental receptor regions for the period 1980-2000 for two seasons: June-August and December-February. The sources of moisture are named on the top panel. These moisture sources were defined on the basis of having annual vertically integrated moisture fluxes (calculated for 1958-2001 using data from ERA 40) above the threshold of 750 mm yr^{-1} (except for the Mediterranean Sea and the Red Sea which were defined using their physical boundaries). Over continents, only areas of markedly positive runoff (precipitation minus evapotranspiration), larger than 0.05 mm d^{-1} are colored. The colors used are those of the corresponding oceanic source region. Overlapping continental regions are plotted with the appropriate sharing mask. The calculations underlying this figure were obtained using forward tracking from the moisture sources defined. This figure and caption are adapted from Gimeno et al. (2012, their Fig. 11, right-side panels).

Figure 3. **Conceptual representation of South America's atmospheric rivers, moist air currents that are brought in by the westerly winds strengthened by forest evapotranspiration (e.g, Kleidon and Heimann, 2000), are deflected by the Andes range, and represent important moisture sources for vast regions throughout the continent, including the La Plata River basin (Byerle and Peagle, 2002). Moisture lost to precipitation over the rainforest returns in large part to the atmosphere through the forest's high evapotranspiration rates, in a repeating cycle ("precipitation recycling") responsible for maintaining high moisture in the atmospheric river as it travels through and out of the Amazon rainforest. Some of the moisture not returned to the atmosphere contributes to replenish the aquifer systems, of which two major ones are represented. The underlying image is from Google Earth. This figure was drawn by NHC and is inspired by a figure in Guimarães and Ramos (2014).**

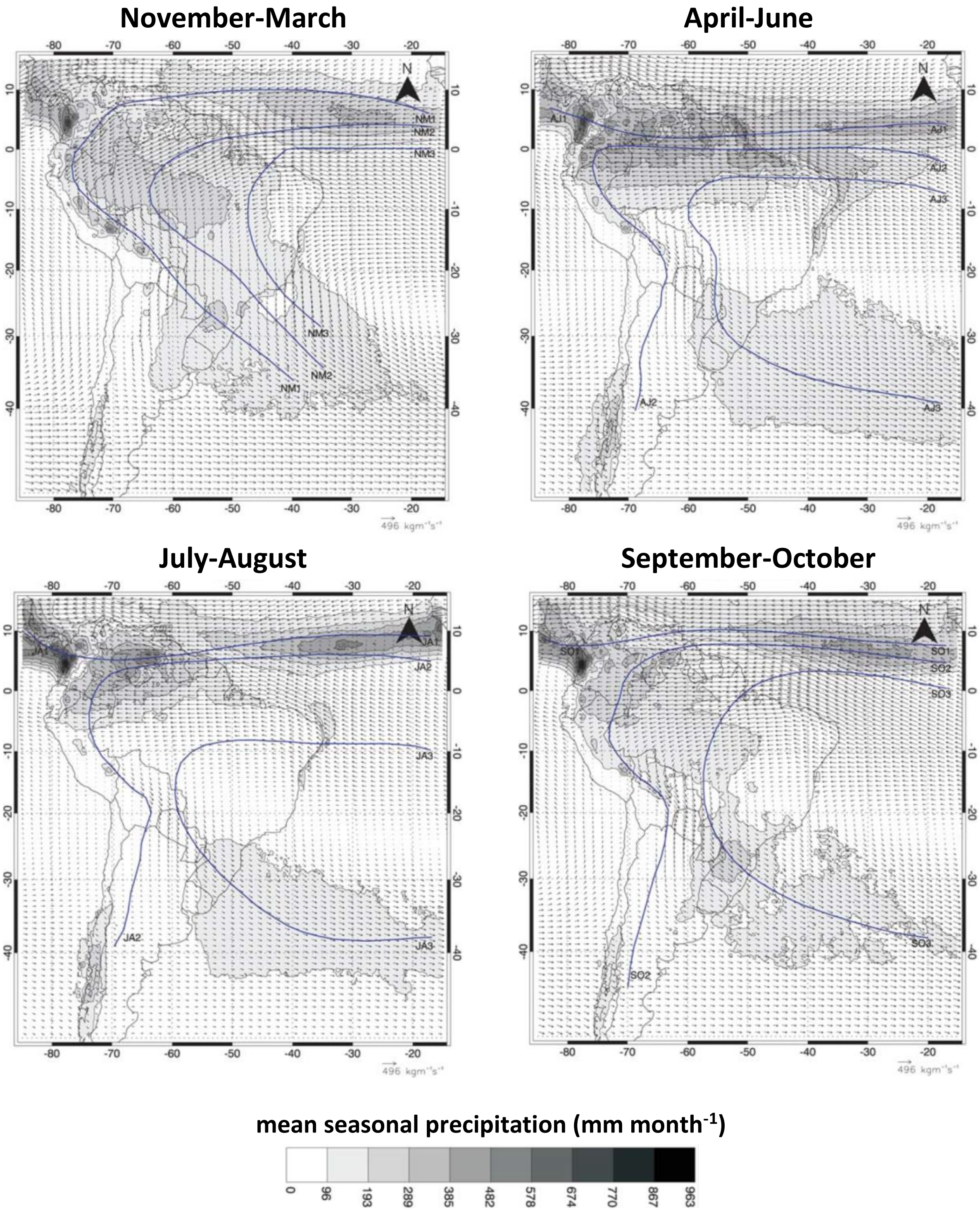


Figure 4. Pathways of aerial rivers in South America east of the Andes along the seasonal cycle of rainfall (mm month-1) for November through March [the wet season], April to June, July to August, and September to October, averaged between 1979 and 2012. Data source: TRMM. This figure and caption are reproduced from Poveda et al. (2014).

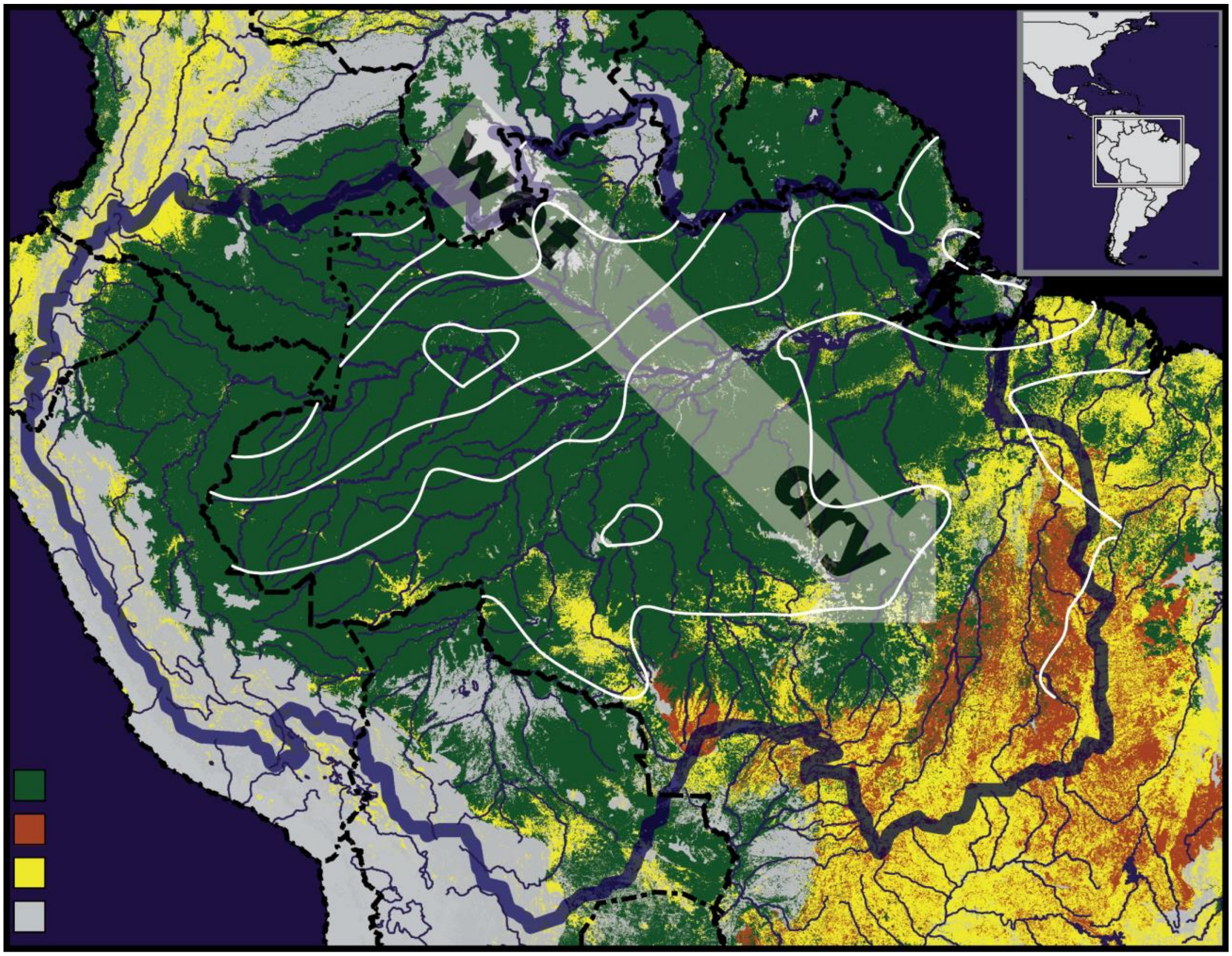


Figure 5. Climatic gradient across the Amazon basin. Main figure, the hydrologic Amazon basin is demarcated by a thick blue line; isopleths of mean daily precipitation during the three driest months of the year (in mm; white lines) (Nepstad et al., 2004) are overlain onto four land-cover classes (key at bottom left) (Eva et al., 2004; Sano et al., 2007). These isopleths are presented only for areas within Brazil, because of lack of adequate data elsewhere. The arrow emphasizes the trend from continuously wet conditions in the northwest to long and pronounced dry seasons in the southeast, which includes Cerrado (savannah/woodland) vegetation. National boundaries are demarcated by broken black lines. Inset, map showing area of main figure (boxed). This figure and caption are reproduced from Davidson et al. (2012).

2.1.2 Evapotranspiration observations from the Large-Scale Biosphere-Atmosphere Experiment in Amazônia (LBA) project

A different class of observational studies, however, seemed indirectly more favorable to the global climate model results. These were the observations of evapotranspiration rates, which consistently report higher values over forest stands compared to shorter vegetation types, the difference being particularly great during the dry season. If forests return more water to the atmosphere, replenishing atmospheric moisture, they can potentially enhance precipitation (e.g., Shukla and Mintz, 1982; Eltahir and Bras, 1994). Bonan (2008) provided an exposition of many of the effects of land cover on climate, through the vegetation's role in mediating moisture, energy, and surface-atmosphere fluxes of trace gases.

The evapotranspiration observations were based on flux tower measurements throughout Brazil, conducted as part of the Large-Scale Biosphere-Atmosphere Experiment in Amazônia (LBA) project – responsible for virtually all existing field measurements of evapotranspiration rates in Brazil, with the global network FLUXNET (www.fluxnet.ornl.gov) offering very few measurements in Brazil. The LBA measurements use the same methodology established by FLUXNET, which is based on measurements of eddy covariance (EC) of turbulent trace gas fluxes (such as CO_2 and water vapor) between vegetation and atmosphere. The LBA measurements cover primarily tropical forests and savannah ecosystems (e.g., Hasler and Avissar, 2007). Very few tropical studies have been conducted in croplands (Sakai et al., 2004) or pastures (von Randow et al., 2004).

LBA's evapotranspiration measurements not only document higher rates for forest, but also demonstrate the role of evapotranspiration in generating a large latent heat flux at the expense of the sensible heat flux, thereby regulating temperature, air humidity, and the stability of the local planetary boundary layer – key factors at the origin of convective rainfall (Rocha et al., 2009). Additionally, the lower albedo of forests also has important effects on the radiative balance (e.g., Gash et al., 1996).

On the basis of LBA's flux tower measurements in Brazil, Rocha et al. (2009) obtained the estimates for evapotranspiration given in Table 2. The lower evapotranspiration rates over pastureland and rice crops, compared to forest and cerrado are evident in Table 2. Differences are especially large in the dry season. Santarém and Manaus are roughly near the 3°S parallel in a region of important tropical evergreen forest cover. For Santarém, dry season rainforest values were 3.3 and 3.9 mm d^{-1} at the two sites, but only 1.9 mm^{-1} for the nearby pastureland. However, for Manaus, the dry season pasture site value, 3.2 mm d^{-1}, was nearly as high as the rainforest value of 3.4 mm d^{-1}. Note also that, although no wet season data are given for Manaus, the data for Santarém indicates that, for cropland, evapotranspiration is at a minimum in the dry season whereas, for forest, it is at a maximum. This is because annual rainfall is high (more than 1,900 mm), and the dry season usually does not exceed 4 months – making solar radiation the dominant control over evapotranspiration for forest. Pasture, however, with its shorter roots, responds to the drier conditions by lowering its evapotranspiration rate.

Solar radiation is the dominant control over evapotranspiration also in the tropical semideciduous forest sites reported in Table 2, located near the 10°S parallel. However, water availability also exerts some control and the dry season evapotranspiration is slightly lower than in the wet season. Peak evapotranspiration thus tends to occur near the transition from the dry to the wet season.

In the remaining group of sites reported in Table 2, the dry season length exceeds 4 months, and mean annual precipitation is below 1,700 mm. Limitations of water availability dictate an evapotranspiration regime with an opposite seasonal pattern relative to the previous sites of tropical evergreen and tropical semideciduous forest. Here, evapotranspiration values are lower year round, and consistently lower in the dry season than the wet season. The Cerrado is characterized by marked seasonal variability in leaf area index and green biomass, associated with a dry season photosynthesis decline, senescence of tree leaves, and grass dormancy (Saleska et al., 2009; Lloyd et al., 2009).

In the floodplain Cerrado, however, where water availability is higher, evapotranspiration rates are also higher and inter-seasonal differences are smaller. This is seen at the Tocantins site in Table 2, where mean evapotranspiration rates are high year round: 3.8 and 3.3 mm d^{-1} in the wet and dry seasons, respectively.

Table 2. Measured mean evaporation rates from the LBA project. Table reproduced (redrawn) from Rocha et al. (2009). The references cited in the table's footnotes are listed in Rocha et al. (2009).

Ecosystem	Site[a]	Measured Mean Evaporation, mm d^{-1}	
		Wet Season	Dry Season
Tropical forest	Manaus K34	2.8 (Nov-Jul)	3.4 (Aug-Oct)
	Santarém K67	2.9 (Dec-Jul)	3.3 (Aug-Nov)
	Santarém K83	3.6 (Dec-Jul)	3.9 (Aug-Nov)
Tropical semideciduous forest	Rondônia JRU	2.8 (Oct-May)	2.6 (Jun-Sep)
	Mato Grosso SIN(5)	3.4 (Jan-May)	3.0 (transition Sep-Oct)
			2.4 (Jul-Oct)
Floodplain (Cerrado)	Tocantins JAV	3.8 (Oct-May)	3.3 (Jun-Sep)
Cerrado s.s	São Paulo PEG	3.0 (Sep-Apr)	1.3 (May-Aug)
	Brasília(6)	3.6 (Jan)	1.7 (Jul-Sep)
Pastureland	Santarém(1)	2.2 (Apr-Jun)	1.9 (Aug-Oct)
	Rondônia(2)	2.9 (Jan-Mar)	2.2 (Jul-Sep)
	Manaus(3)	-	2.5 (Oct)
	Manaus(4)	-	3.2 (Jul-Sep)
Rice crop	Santarém(1)	2.7 (Mar-Jun)	-
Bare soil	Santarém(1)	-	1.2 (Nov-Dec)

[a] Reports referenced are noted in parentheses: 1, *Sakai et al*. [2004]; 2, *von Randow et al.* [2004]; 3, *Wright et al.* [1992]; 4, *da Rocha et al.* [1996]; 5, *Vourlitis et al.* [2002]; and 6, *Miranda et al.* [1996].

2.2 Three mechanisms by which land cover affects rainfall: Moisture recycling, local coupling, and atmospheric circulation

Water's fluxes and phase transitions play a major role in the land surface-atmosphere fluxes and budgets of heat, momentum, and radiation. Therefore, changes to seasonal evapotranspiration rates resulting from land cover changes can be expected to modify the atmosphere's local thermal structure (the term used is "local coupling") and influence its large-scale circulation – two mechanisms that are often overlooked or ignored in studies of climatic impacts of land cover change.

Figure 6 is reproduced from Goessling and Reick (2011) and represents schematically the three major mechanisms by which evapotranspiration (and its changes due to land cover changes) may affect precipitation: (I) Moisture recycling; (II) Local coupling; and (III) Circulation. Importantly, the three mechanisms in Figure 6 act on different spatial scales, and they also depend on the spatial scale of the land cover perturbation. Local coupling acts on relatively small spatial scales, but moisture recycling and atmospheric circulation operate on large spatial scales (Goessling and Reick, 2011). Changes mediated by the large-scale circulation are not restricted to the same geographical region where the evapotranspiration changes took place (as in case of the local coupling) or regions along the downwind trajectories (as in case of moisture recycling), but can in principle occur anywhere in the globe (Goessling and Reick, 2011). Climatic effects occurring remotely from the source of perturbation are known as "teleconnections".

The three mechanisms in Figure 6 differ not only in their spatial scale of influence but also in the magnitude and even the sign of their impacts on precipitation. In mechanism I, moisture recycling (section 2.2), changes in evapotranspiration (due for example to changes in land cover) lead to precipitation changes of the same sign ("positive coupling"). Increased evapotranspiration (resulting e.g. from forestation) can only lead to increased precipitation, and decreased evapotranspiration (resulting e.g. from deforestation) can only lead to decreased precipitation. This is not the case for mechanism II, local coupling (section 2.3), where an increase in evapotranspiration can lead either to an increase or a decrease in precipitation, and the same can be said of a decrease in evapotranspiration. In the case of mechanism III, atmospheric circulation (section 2.4), evidence is for positive coupling, with high evapotranspiration rates from forests contributing maintaining large-scale circulation patterns that bring moist air in their direction, replenishing the losses to runoff.

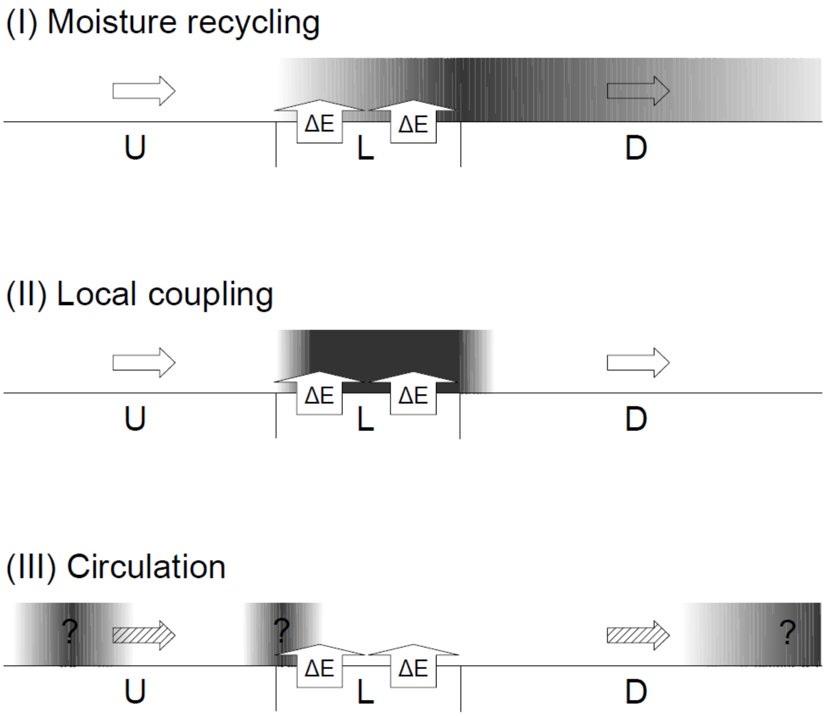


Figure 6. **Schematic of three mechanisms via which evaporation affects precipitation. The effect of each mechanism is shown isolated from the others. The arrows pointing to the right indicate the wind direction. The color gradients indicate the regions where precipitation responds (either positively or negatively). U= upwind region, L = local region, D= downwind region, ΔE = imposed evaporation anomaly. (I) Moisture recycling: The precipitation response, caused by changes to the atmospheric moisture budget, grows gradually over the region of the imposed evaporation anomaly, then decays (slowly) over the downwind region. (II) Local coupling: The precipitation response, caused by changes to the thermal structure of the atmosphere, collocates with the imposed evaporation anomaly. A slight downwind shift is indicated because the structural change may need some time to develop. (III) Circulation: The precipitation response may occur anywhere, caused by changes to the 3-D large-scale atmospheric circulation (indicated by the hatching of the wind-arrows). While mechanism (I) accounts for the effect of ΔE on the vertically integrated atmospheric moisture budget, mechanisms (II) and (III) account for modified energetics that come along with ΔE (in particular changes in temperature). This figure and caption are reproduced from Goessling and Reick (2011).**

From their experiments with climate models, Goessling and Reick (2011) concluded that "*The key for understanding the response of precipitation to an evaporation anomaly may lie in local coupling [mechanism II] if the scale of perturbation is sufficiently small, but at large scales moisture recycling and the large-scale circulation [mechanisms I and III] come into play*."

Recognizing the presence of three different mechanisms operating at different spatial scales helps provide an explanation for the long-standing apparent disagreement between climate model simulations and observations. Climate models simulate declines in regional precipitation as a response to large-scale tropical deforestation, even though the magnitude of the decline varies with the model (Hasler et al., 2009; Pitman et al., 2009) and its spatial and temporal resolution (Ramos da Silva et al., 2008). Such model results emerged clearly in the 1980s (e.g., Henderson-Sellers and Gornitz, 1984; Lean and Warrilow, 1989; Nobre et al., 1990), and persist in today's models, where the representation of land-atmosphere interactions is improved in its spatial, temporal, and dynamical detail (Nobre et al., 2009; Hasler et al., 2009; Ramos da Silva et al., 2008; and Werth and Avissar, 2002). In contrast with global climate models, some rainfall observations have reported trends over time towards increasing – rather than decreasing – precipitation over deforested or non-forested areas, and higher rainfall over deforested areas compared to adjacent forested areas (Butt et al., 2011; Chagnon and Bras, 2005; Negri et al., 2004).

We can explain these observations invoking mechanism II, local coupling, where the increased surface heating in non-forested areas promotes the local ascent of air masses, leading to convective precipitation as well as lowered air pressure. The lowered pressure then draws in moist air from neighboring forested areas, which has a high moisture content because of the forests' promotion of moisture via mechanisms I and III (moisture recycling and circulation).

2.3 Mechanism I: Moisture Recycling

Moisture recycling has long been recognized as a major component of the Amazon River basin's hydrology (Matsui et al., 1976; Salati et al., 1979; Eltahir and Bras, 1996; Trenberth, 1999; Bosilovich et al., 2005; Burde et al., 2006; Dirmeyer and Brubaker, 2007; van der Ent et al., 2010; Goessling and Reick, 2011; Ellison et al., 2012; Spracklen et al., 2012). Most of the evapotranspiration flux is composed of transpiration, while evaporation represents a smaller fraction (Jasechko et al., 2013).

The above listed studies used diverse methodologies, ranging from isotope studies (e.g., Salati et al., 1979) to quantitative analysis (e.g. Eltahir and Bras, 1994). Estimates of what percentage of Amazon's precipitation is composed of Amazon's evapotranspiration (the "recycled precipitation" percentage $P_{Recycled}/P_{Total}$), as opposed to moisture advected from outside the Amazon (especially the oceans), have varied in the range 20-27% as a spatial average (Costa and Foley, 1999; Eltahir and Bras, 1996; Bosilovich and Chern, 2006; and Brubaker et al.,1993). Values for specific locations differ from this overall average. Values of $P_{Recycled}/P_{Total}$ are lowest near the coast, where most of the air moisture is of oceanic evaporation origin, and increase towards the interior. Generally speaking, $P_{Recycled}/P_{Total}$ increases along atmospheric trajectories over the Amazon (Lattau et al., 1979; Eltahir et al., 1994; Trenbert et al., 2003). $P_{Recycled}/P_{Total}$ estimates offered by these studies are approximately 50% in the southwestern Amazon, declining to 10% in the eastern Amazon. The regional climatic gradient evolves from wetter to dryer in this direction (Figure 5). Specific value estimates obtained in different studies are listed in Ellison et al. (2012).

The recent study by Spracklen et al. (2012) used a novel methodology to demonstrate the magnitude of remote effects of land cover on precipitation. Spracklen and colleagues modeled the atmospheric trajectories worldwide, to represent the pathways along which moisture is transported. They then analyzed satellite observations of rainfall (from the Tropical Rainfall Measuring Mission and other satellites; Huffman et al., 2007) and land cover (based on leaf area index estimates from the Moderate Resolution Imaging Spectroradiometer, MODIS; Myeni et al., 2002). Their period of study was 2001-2007. Spracklen and colleagues found that air masses which, according to the modeled trajectories, have traveled over extensive forested areas over a few days' time, on average produce at least twice as much rainfall as air masses of similar origin that traveled over mostly non-forested areas. They demonstrated this result for more than 60% of the global tropical land surface (defined as being comprised in 30°S-30°N). Spracklen et al. thus developed empirical relationships relating rainfall to the preceding along-trajectory landcover, and concluded that *"this empirical correlation is consistent with evapotranspiration maintaining atmospheric moisture in air that passes over extensive vegetation."*

Further, Spracklen and colleagues used these empirical relationships to explore rainfall changes associated with hypothetical future loss of forest over the Amazon region. Assuming that the recent rates of Amazon deforestation would persist until year 2050, the resulting estimates are for about 40% deforestation of the Amazon (Soares-Filho et al., 2006, cited by Spracklen et al., 2012). Under this deforestation assumption, Spracklen and colleagues estimated, for the wet season, an average 12% rainfall decline; and for the dry season, an average 21% rainfall decline over the Amazon region (Figure 7). These are regional averages, and localized values may be larger or smaller. Spracklen and colleagues note that these values are roughly similar to the severe Amazon-wide drought experienced in year 2010, and suggest that conditions similar to 2010 might become normal by mid-century. Spracklen and colleagues also note that their estimates are *"broadly consistent with"* the results of climate models (e.g., Nobre et al., 2009; Hasler et al., 2009; Ramos da Silva et al., 2008; and Werth and Avissar, 2002).

Studies by Phillips et al. (2009) and Aragão et al. (2007) suggest that, were rainfall declines do occur such as those projected by Spracklen et al. (2012), the drier average conditions would threaten the remaining Amazon forests. They would also carry major implications for ecology, agriculture and hydroelectric power generation – the source of 65% of Brazil's electricity (Aragão, 2012, citing BAEE, 2012). Aragão (2012) suggests that the future deforestation scenario considered by Spracklen et al. (2012) is likely to be excessive because, Aragão writes, *"Brazil is committed by its National Plan on Climate Change to limit historical deforestation rates by 80% by the year 2020 [Nepstad et al., 2009]".* In turn, Nobre (2014) is less optimistic in light of Brazil's 2011 Forest Code's amnesty attitude towards violators.

Spracklen and colleagues comment that, even though air generally becomes drier during atmospheric transport over land compared to oceans, air masses are able to remain moist over densely vegetated regions, because while atmospheric moisture is depleted by precipitation, it is in turn replenished by evapotranspiration (which 70-90% of the time occurs during daytime), in a repeating "recycling" of precipitation water. Aragão (2012), in an commentary article published in the same journal issue as the Spracklen et al. (2012) article, created the illustration reproduced in Figure 8.

It is important to recognize that the *downwind*, i.e. *non-local* nature of the rainfall effects documented by Spracklen et al. (2012). In their manuscript, Spracklen and colleagues write that *"These processes operate on timescales of days over distances of 100-1,000 km [van der Ent et al., 2010] such that large-scale land-use change may alter precipitation hundreds to thousands of kilometers from the region of vegetation change."* Indeed, their above-cited estimates for year 2050, associated with a 40% deforestation of the Amazon region, result in a projected 4% rainfall decline in the geographically removed Rio de la Plata basin.

An important point is that the results reported by Spracklen et al. (2012) cannot be directly attributable to moisture recycling alone, and Spracklen and colleagues did not consider or attempt to rule out the possibility that mechanism III may be implicated. This point was not missed by proponents of mechanism III. Makarieva et al. (2014) challenged the recycling-based interpretation and proposed that the data reported by Spracklen et al. (2012) was consistent with the biotic pump theory (Makarieva and Gorshkov, 2007), which is one of the existing theories attempting to represent mechanism III (see section 2.5).

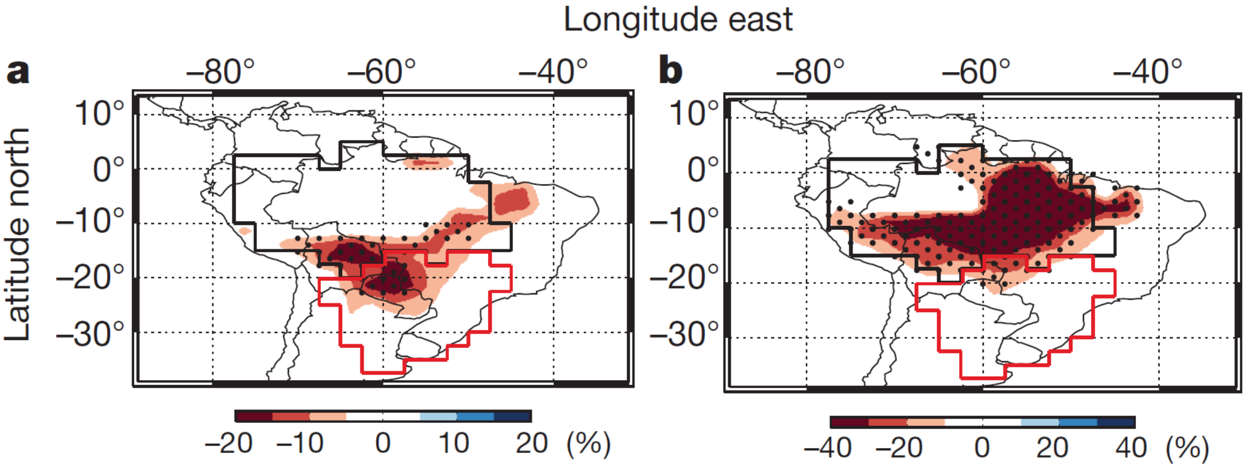


Figure 7. **Simulated percentage change in precipitation due to 2000-2050 business-as-usual deforestation of the Amazon basin. A, Wet season; b, dry season. Stippling denotes regions where the simulated precipitation anomaly differs from the present-day (1998-2010) rainfall by more than 1 [standard deviation]. The Amazon (black) and Rio de la Plata (red) basins are marked. This figure and caption are reproduced from Spracklen et al. (2012).**

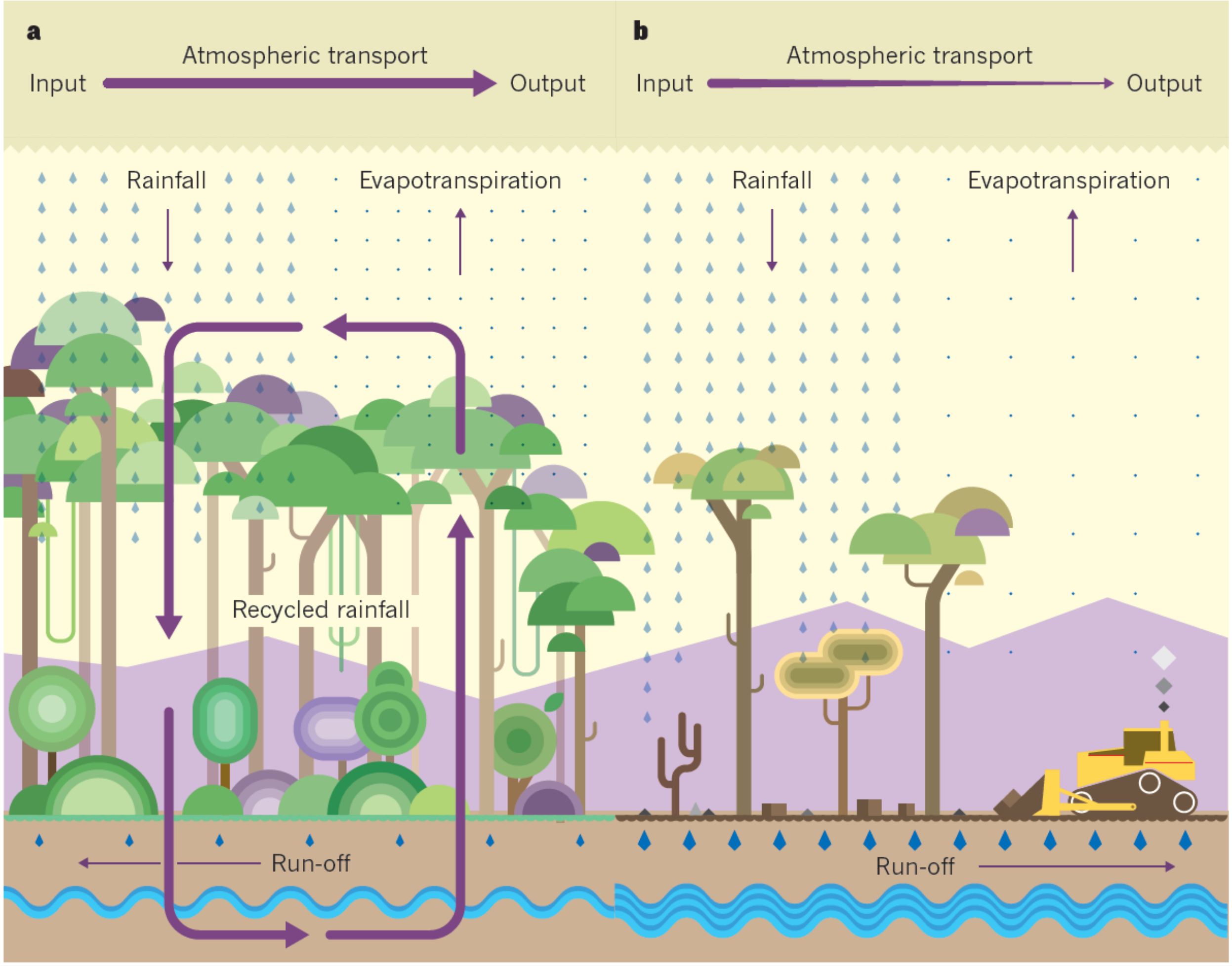


Figure 8. **Effects of deforestation on rainfall in the tropics. a, Much of the rainfall over tropical forests comes from water vapor that is carried by the atmosphere from elsewhere. But a large component is 'recycled' rain – water that is pumped by trees from soil into the atmosphere through a process called evapotranspiration. Water exits from forests either as runoff into streams and rivers, or as evapotranspirated vapor that is carried away by the atmosphere. The atmospheric transport of water vapor into the forest is balanced by the exit of water in the form of vapor and runoff. b, Spracklen and colleagues' analysis (Spracklen et al., 2012) suggests that deforestation reduces evapotranspiration and so inhibits water recycling. This decreases the amount of moisture carried away by the atmosphere, reducing rainfall in regions to which the moisture is transported. Decreasing evapotranspiration may also increase localized runoff and raise river levels. This figure and caption are reproduced from Aragão (2012).**

2.4 Mechanism II: Local Coupling

Research studies focused on mechanism II, local coupling, were reviewed by Seneviratne et al. (2010). They conclude that *"The key for understanding soil moisture-precipitation interactions lies more in the impact of soil moisture anomalies on boundary-layer stability and precipitation formation than in the absolute moisture input resulting from modified evapotranspiration."* It is only at larger spatial scales that moisture recycling and large-scale atmospheric circulation dominate the climatic effects of land cover perturbations. The physical mechanisms involved in the local coupling between land and atmosphere are varied and complex, and our current understanding of them is limited. Our ability to accurately represent them mathematically is also limited, though major research projects have been dedicated to the task, notably the Global Land/Atmosphere System Study (GLASS), and the Global Land-Atmosphere Coupling Experiment (GLACE) (e.g., Koster et al., 2006), and large improvements in process representation have been incorporated into the latest generation of global and regional climate models.

Seneviratne et al. (2006) showed that negative correlations between evapotranspiration and land surface temperature, denoted ρ(E,T) can be used to identify regions where there is strong coupling between the land surface and the atmosphere (Figure 9). This is the case over the Amazon forest during the dry season (Wang et al., 2011).

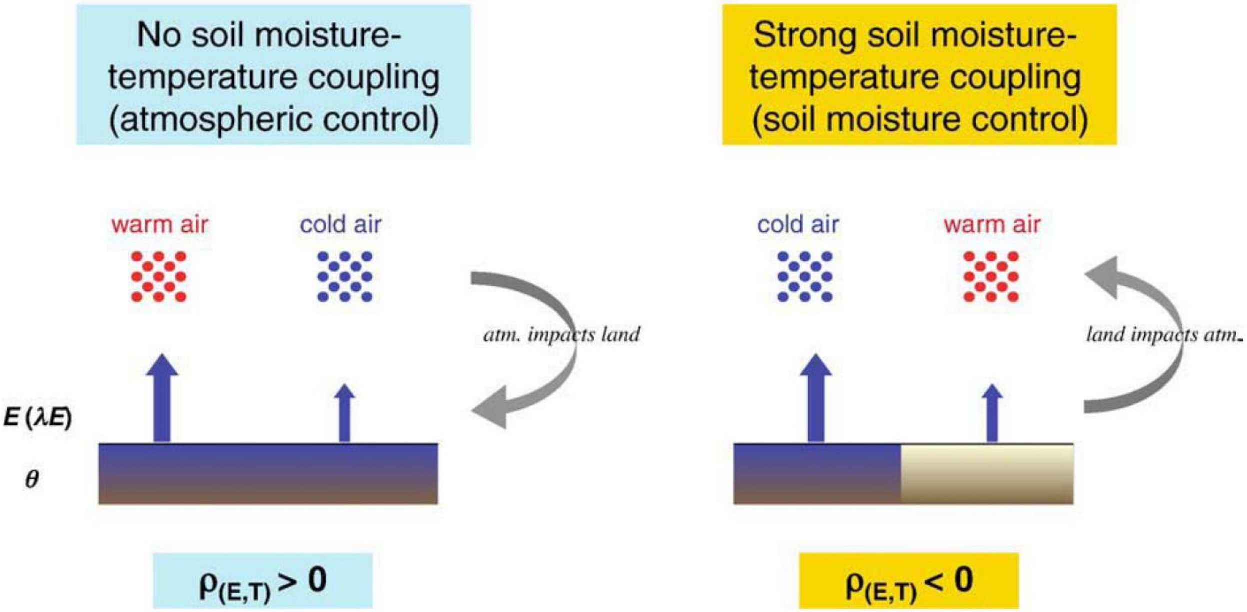


Figure 9. When evapotranspiration is not limited by soil moisture but only by available energy (left image), the state of the atmosphere affects the land surface but not the reverse. When evapotranspiration is strongly limited by soil moisture (right image), then evapotranspiration affects the atmosphere and influences local precipitation. ρ(E,T) denotes the correlation between evapotranspiration and temperature. This figure is reproduced from Seneviratne et al. (2010).

Small-scale land cover changes may alter precipitation locally through changes in the thermodynamic profile and the development of surface-induced mesoscale circulations (Garcia-Carreras et al., 2011; Wang et al., 2000). The changes in the albedo associated with different land covers are also important, as shown in theoretical and modeling studies (Dirmeyer and Shukla, 1994; Zeng and Neelin, 1999; Berbet and Costa, 2003). Afforestation is associated with lower albedo (α), increased atmospheric turbulence (higher z_0), increased leaf area index (LAI), and increased root depth (z_R). The increases in z_0, LAI, and z_R all contribute to an increase in latent heat flux, atmospheric instability, cloudiness, and precipitation. The lowered albedo, together with cloud-radiative feedbacks, result in less of the incoming radiation is reflected and more is absorbed. This leads to higher surface latent and sensible heat fluxes and warms the atmospheric column, which results in increased convection, cloudiness and precipitation. The cloud-radiative feedback is an important factor, as it modulates the amount of incident solar radiation at the surface (Berbet and Costa, 2003).

Measurements of these variables for different land covers were obtained during the mesoscale atmospheric campaigns of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) Program, a component of the TRMM satellite validation campaigns. For example, results of the January-February 1999 campaign in Rondônia, reported in Silva Dias et al. (2002; tables 1 and 2 therein) document the larger net radiation for the forest sites compared to pasture. The lower incoming solar radiation and higher incoming long wave radiation reaching the forest were indicative of a more cloudy atmosphere. Higher air moisture and air temperature were also found over forest cover. The evapotranspiration of the forest was about 0.6 mm day-1 larger than that of the pasture. These measurements were taken in wet season months (January and February). The corresponding dry season difference in evapotranspiration rates between land covers can be expected to be higher.

There may also be a role played by condensation nuclei by substances emitted by vegetation species as well as pyrogenic emissions, although these processes are not sufficiently understood (Andreae et al., 2004; Koren et al., 2012). According to Pöschl et al. (2010) (see Figure 10), biogenic volatile organic compounds (BVOCs; such as isoprene, terpenes, etc), when in presence of high atmospheric humidity and solar radiation, oxidize and precipitate into an extremely fine suspended dust that is hydroscopic (i.e., attracted to water molecules). This biogenic dust offers extremely efficient condensation nuclei for cloud formation. Before these BVOCs have a chance to precipitate, they are present as gases, which are not removed from the atmosphere by rainfall. Thus, the atmosphere above the rainforest always contains BVOCs for forming new condensation nuclei.

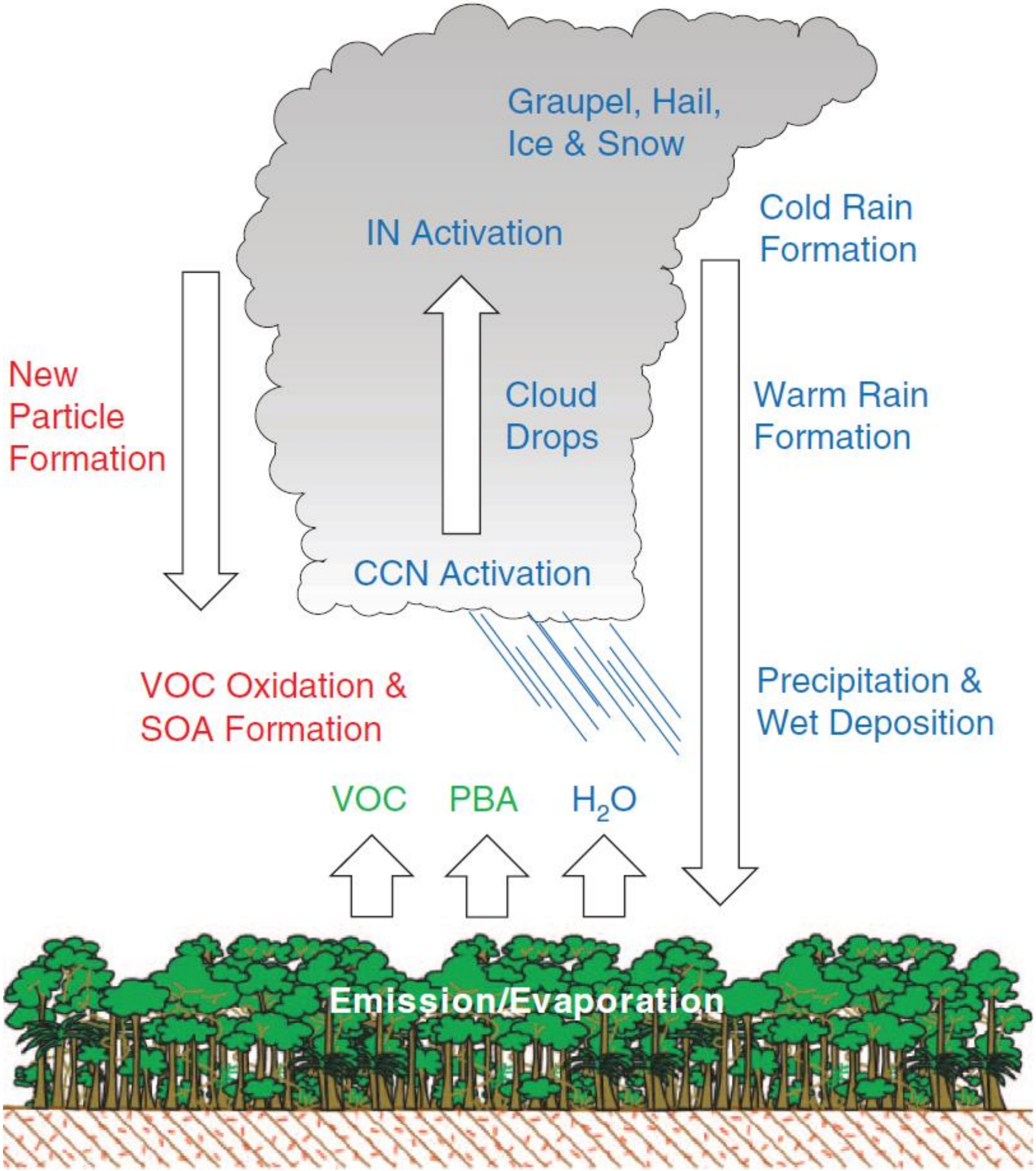


Figure 10. **Aerosol and water cycling over the pristine rainforest. SOA [secondary organic aerosols] formed by photo-oxidation of volatile organic compounds (VOC) and PBA [primary biological aerosols] emitted from biota in the rainforest (plants and microorganisms) serve as biogenic nuclei for CCN [cloud condensation nuclei] and IN [ice nuclei], which induce warm or cold rain formation, precipitation, and wet deposition of gases and particles. This figure and caption are reproduced from Pöschl et al. (2010).**

2.5 Mechanism III: Atmospheric Circulation

That changes in evapotranspiration in tropical forested regions are capable of altering large-scale atmospheric circulation patterns and intensity, thereby causing changes in precipitation, has been recognized at least since Riehl and Malkus's (1958) manuscript. Riehl and Malkus characterized tropical South America as a major center of convective activity (mostly developed within large cumulonimbus clouds) that continuously releases heat into the atmosphere, thereby influencing the Hadley-Walker circulation and the global circulation. The Hadley-Walker circulation represents the global conveyor belt that redistributes water and energy from the tropics to the subtropics.

A variety of supporting evidence for mechanism III was presented by Poveda and Mesa (1997), Pielke et al. (1998), Kleidon and Heimann (2000), Gorshkov et al. (2000), Foley et al. (2003), Gorshkov et al. (2004), and Goessling and Reick (2011), among others. Kleidon and Heimann (2000) performed global climate model experiments in which they changed the land cover over tropical South America. They found that the forested land cover, due to its higher evapotranspiration rates, results in a strengthening of the Hadley-Walker circulation to the benefit of rainfall over the forest. This difference in evapotranspiration rates between forests and shorter vegetation cover is especially large during the dry season, because the trees' deeper roots are able to access groundwater reserves that are not accessible to shorter vegetation. Figure 11, reproduced from Kleidon and Heimann (2000), illustrates this circulation strengthening in the dry season over tropical forested regions.

Kleidon and Heimann (2000) conclude that "*deep rooted vegetation is an important part of the tropical climate system*" and, based on their global climate model simulations, they report that "*Without the consideration of deep roots, the present-day surface climate cannot adequately be simulated*." These authors pointed to deficiencies in the global climate models of their time where land surface parametrizations generally used rooting depths of less than 2 meters, in contrast to some observations reports roughly ten times greater. The higher evapotranspiration rates from forest versus shorter vegetation cover at different locations in Brazil were documented in LBA's flux tower experiments (Table 2).

More recently, Goessling and Reick (2011), using a global climate model to conduct an extreme experiment where all continental evapotranspiration was eliminated worldwide, showed major resulting changes in the global Hadley circulation and associated changes in the strength and position of the inter-tropical convergence zone (ITCZ) – a key influence on South American precipitation. They report large simulated declines in precipitation over most of South America, and they emphasize that mechanism I (moisture recycling) is not sufficient to explain these results, which illustrate the importance of mechanism III. Contributions from mechanism II (local coupling) are also important.

A particularly clear illustration case for mechanism III was recently documented by Poveda et al. (2014). Figure 12, reproduced from Poveda et al. (2014), shows the average horizontal wind velocity at the atmospheric pressure level of 925 hPa at different times of year. The source of the (gridded) wind data is the ERA-Interim reanalysis, and the averaging period is 1979-2012. We see in the figure, for all times of year, that two major low-level jets of different geographic origins – the CHOCO, in red, and the

Caribbean CLLJ, in blue – deviate from their paths to converge onto western Colombia, a densely forested region which holds the world record for mean annual rainfall (exceeding 12,500 mm). Poveda et al. (2014) remark that, while the curving of the CHOCO jet to the east can be explained by the sea surface temperatures gradient between the Ecuador-Peru cold tongue and the warmer Colombian Pacific and is favored by the cross-equatorial trade winds' change of direction to the east after crossing the Equator at this longitude, none such mechanisms explain the curvature to the southeast of the Caribbean LLJ across the Apanama Isthmus, before merging with the CHOCO jet.

Poveda et al. (2014) suggest that the explanation for the curvature to the southwest of the Caribbean LLJ lies with mechanism III. The precise physical processes underlying mechanism III are left more in the open, when they write (quoted from Poveda et al., 2014, p. 99): *"It could be explained by (1) surface convergence favored by the release of latent heat in the region's extraordinarily intense storms and mesoscale convective systems and (2) atmospheric pressure gradients created by the condensation of water vapor evapotranspired by the tropical rainforest of the Chocó-Darién region of western Colombia."* Possibility (1) corresponds to the more traditional explanation for mechanism III, such as is encoded in climate models like that used in the Goessling and Reick (2011) experiments, for example. Possibility (2) corresponds to the biotic pump theory of Makarieva and Gorshkov, reviewed below. Both possibilities (1) and (2) represent alternative, though not mutually-exclusive (they can co-exist) explanations for mechanism III.

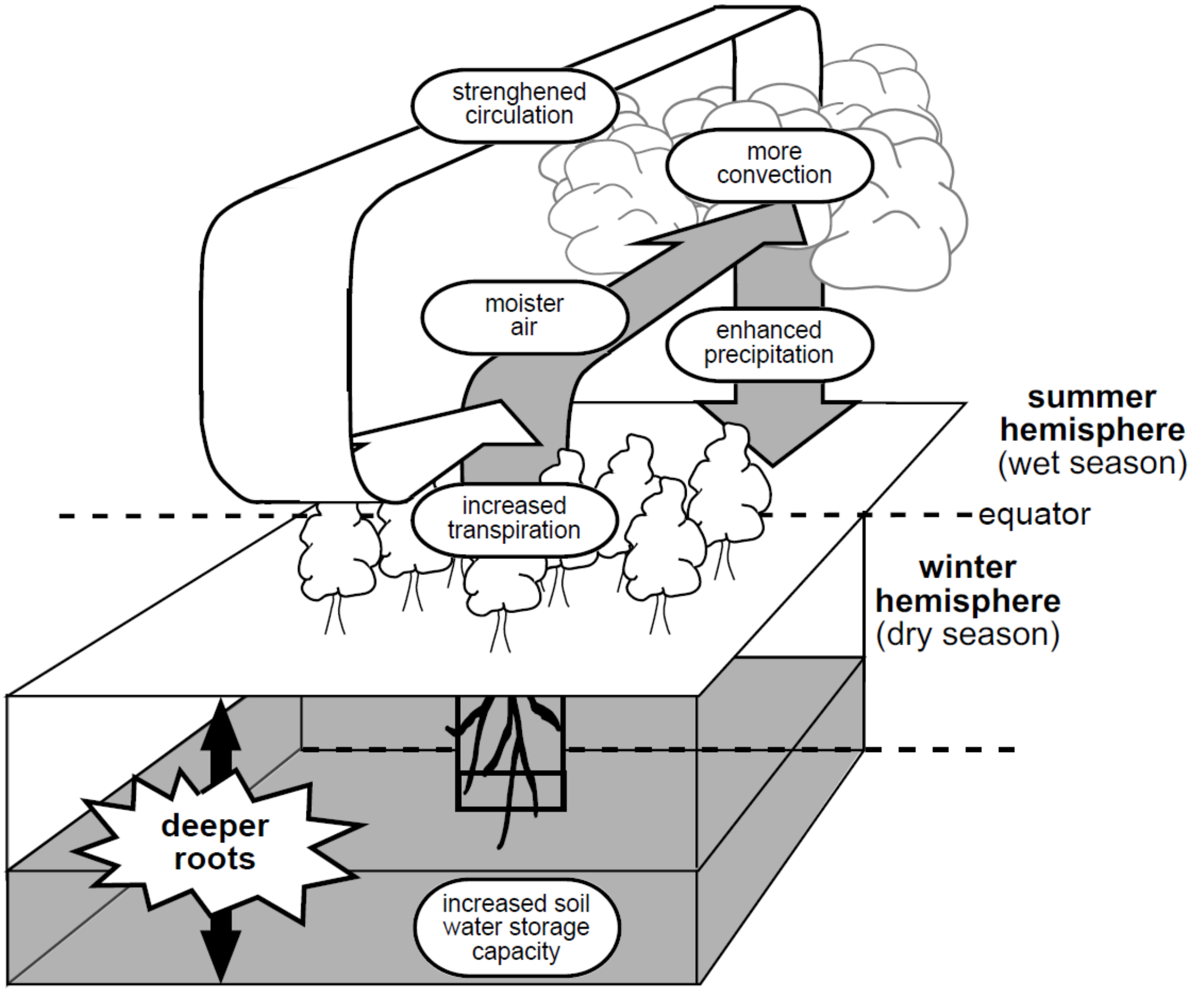
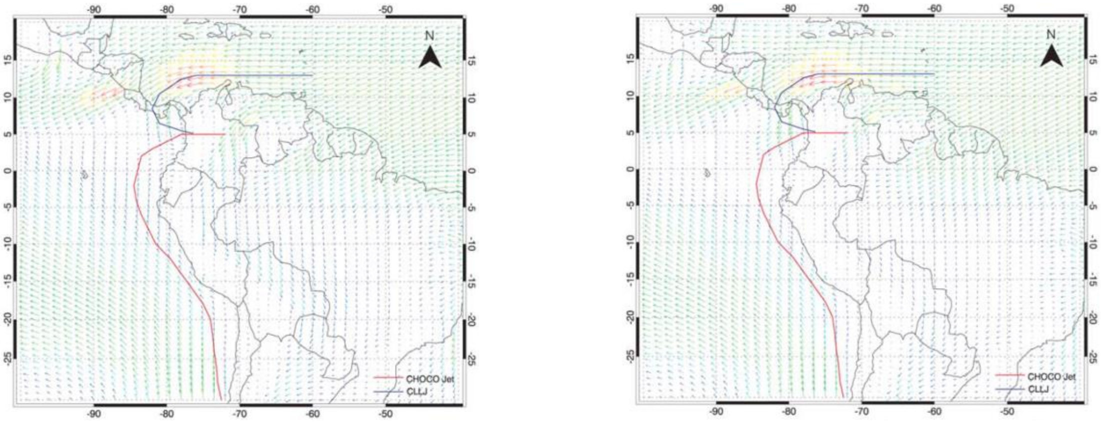


Figure 11. **This figure illustrates the effect of deep rooted vegetation (increased rooting depth) on the atmosphere. Deep roots provide an increased soil water storage capacity which increases the access to water stored in the soil for dry periods. Consequently, transpiration is generally enhanced during the dry season leading to local cooling and moister air. This way, more moisture (and energy) is transported to the inner tropical convergence zone resulting in enhanced precipitation on the other hemisphere and a generally strengthened circulation. The shaded areas denote water. This figure and caption are reproduced from Kleidon and Heimann (2000).**

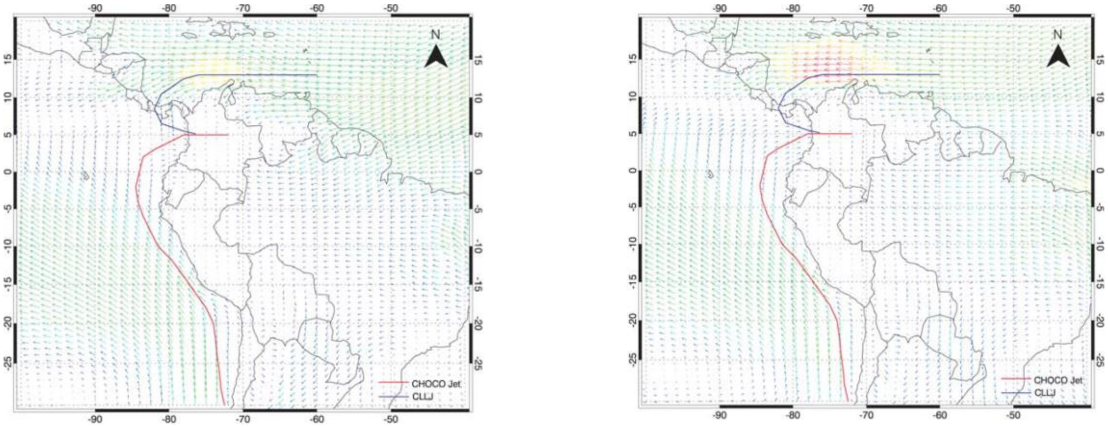
December-January

February-March



April-May

June-July



August-September

October-November

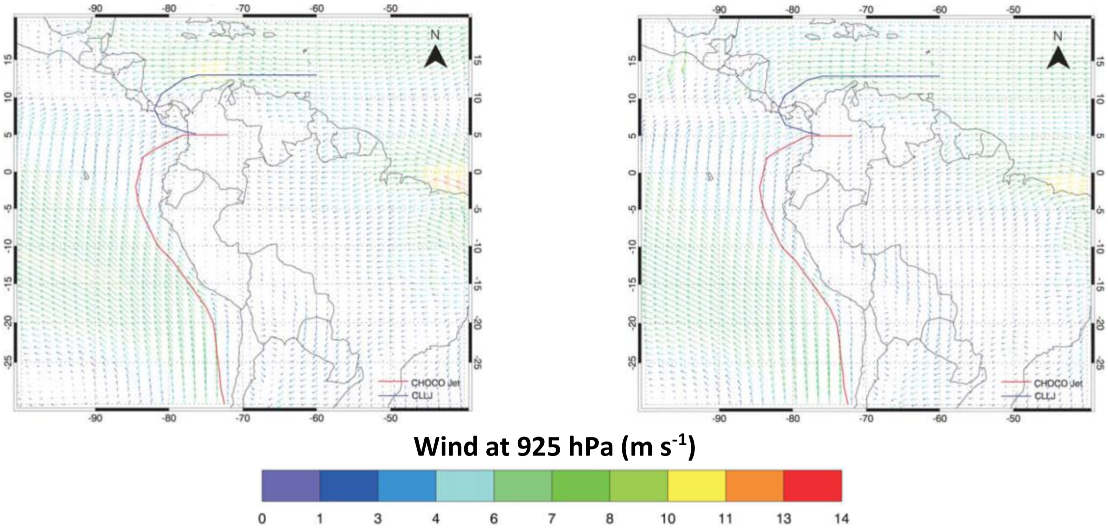


Figure 12. **Seasonal cycle of average 925 hPa horizontal wind velocity (m s^{-1}) over South America during 1979-2012. Notice the recurvature of the CHOCO low-level jet toward the east after crossing the Equator, and the recurvature of the Caribbean low-level jet (CLLJ) toward the southeast after crossing the Panama isthmus, both converging on the world-**

record rainfall region of western Colombia. Data source: ERA-Interim reanalysis. This figure and caption are reproduced from Poveda et al. (2014). A new “biotic pump” theory emerged recently, in a series of manuscripts led by A. Makarieva and V. Gorshkov, where the main driving force for atmospheric circulation is not the release of heat associated with evapotranspiration – as in previous explanations for mechanism III – but the drop in air pressure associated with condensation. The key driving force in previous studies (referenced above) is the release of heat into the atmosphere associated with evapotranspiration. This is consistent with the current prevailing scientific understanding of global atmospheric circulation as primarily driven by horizontal gradients of air pressure associated with surface temperature gradients, combined with effects of the earth’s rotation. The implication of the Makarieva and Gorshkov’s theory is that spatial differences in evapotranspiration rates give rise to stronger spatial gradients of air pressure than do differences in surface temperature.

The biotic pump theory was given a mathematical formulation based on physical principles, in Makarieva and Gorshkov (2007) and Makarieva et al. (2013). In this theory, forests attract moist air masses toward themselves by increasing their own evapotranspiration rates, which leads to air saturation and condensation with a concomitant drop in air pressure. The lowered air pressure pulls in new, moist air masses – thus acting as a biotic pump for oceanic moisture that provides a positive feedback to precipitation. Air saturation is achieved with even small increases in evapotranspiration rates because the air above tropical forests is kept close enough to saturation as a result of moisture recycling (our mechanism I) and circulation (mechanism III itself).

The biotic pump theory as formulated by Makarieva and Gorshkov yields more powerful horizontal atmospheric pressure gradients than previous formulations referenced above, which were based on heat transfer from land surface to atmosphere. The theory generated controversy, and its theoretical formulation was challenged by Meesters et al. (2009), receiving a response in Makarieva and Gorshkov (2009b). Of course, theirs is only one theory concerning a novel physical basis for mechanism III, but the existence of mechanism III is not controversial because well-accepted thermodynamic principles based on temperature gradients are sufficient to support it, and because of observational evidence.

All formulations of the forces driving mechanism III – either the more traditional formulations based on the atmosphere’s thermal gradients, or those unrelated to the biotic pump theory as formulated by Makarieva and Gorshkov – have far-reaching consequences for science and policy at a global scale. But because of this mechanism’s importance, it is deserving of intense further research leading to the scrutiny of its theoretical components, and rigorous testing using observational evidence, with the goal of establishing a resilient theory. One of the consequences of mechanism III, with particularly major consequences to forest policy worldwide, is that the high evapotranspiration rates associated with a densely forested region bring in humid air masses and, therefore, the elimination of these forests would lead to much drier conditions – which, eventually, would preclude future forest regrowth, originating a stable new dry climate.

A brief review of the historical antecedents of the biotic pump theory is given in Makarieva et al. (2013), and goes back to Deluc (1812) – who mentioned that moisture condensation creates an “airfree” space that may cause wind gusts. The history continues through various modern researchers who associated condensation and precipitation with lowered air pressure (Lorenz, 1967, Eq. 86; Trenberth et al., 1987; Trenberth, 1991; Gu and Qian, 1991; Qiu et al., 1993; van den Dool and Saha, 1993; Ooyama, 2001; Schubert et al., 2001; Wacker and Herbert, 2003; Lackmann and Yablonsky, 2004; Wacker et al., 2006).

Observational evidence favorable to the biotic pump theory was presented by Makarieva and Gorshkov (2007), Makarieva et al. (2009), Makarieva et al. (2013), Makarieva et al. (2014), Poveda et al., (2014), and Molina et al. (2014). The results obtained by Spracklen et al. (2012) (reviewed in section 2.3), which were originally interpreted by Spracklen et al. in light of rainfall recycling (mechanism I) were re-interpreted by Makarieva et al. (2014) in light of the biotic pump theory. A subset of the evidence presented in these various publications is reviewed below. In the view of the authors of this literature review, a thorough exploration of alternative explanations for the observations presented nevertheless remains lacking; and contentious aspects (Meesters et al., 2009) of the original mathematical formulation in Makarieva and Gorshkov (2007) have not been sufficiently resolved by observational evidence. Sheil and Murdiyarso’s (2009) manuscript entitled *“How forests attract rain: An examination of a new hypothesis”* published as a *Forum* article in the journal *BioScience*, provided favorable commentary to the biotic pump theory, but not a rigorous examination. Nobre (2014) suggested that the Sheil and Murdiyarso (2009, p. 17) publication reflected the theory’s gaining of acceptance in the scientific community.

Makarieva and Gorshkov (2007) used data from the International Geosphere Biosphere Program (IGBP) to demonstrate that mean seasonal precipitation rates decline exponentially with distance from the ocean in a few non-forested terrestrial transects studied; whereas a few forested transects studied exhibit intense precipitation even at great inland distance. In a follow-up manuscript, Makarieva et al. (2009) studied additional continental transects: seven transects in mostly forested regions, and five transects in mostly non-forested regions. The forested regions studied included the world’s six largest river basins that maintain major forest cover, all larger than a million km^2 (the Amazon, Congo, Ob, Mackenzie, Yenisei and Lena river basins), and an east-to-west 40°N transect of North America from its Atlantic coast (Figure 13). They found that precipitation declines in the inland direction in all five non-forested transects, but in only two of the mostly forested transects – the North-American transect and the Ob River basin. In the latter two cases, the precipitation decline with distance was markedly slower than in the non-forested transects (Figure 14). This result is interpreted by these authors on the basis of the biotic theory: *“the forest evaporation flux supports ascending fluxes of air and ‘sucks in’ moist air from the ocean”* (quoted from Makarieva and Gorshkov, 2007).

Poveda et al. (2014) used the atmospheric river pathways they identified (shown previously in Figure 4) to test the predictions of the biotic pump theory (which they designate BiPAM theory) against the TRMM satellite-based rainfall dataset. The atmospheric river pathways are displayed again in Figure 15, this time over the land cover map of South America by Eva et al. (2004). Rainfall rates are plotted with distance along each of these pathways, in Figure 16. Over humid and temperature forests, the rainfall rates do not decline with distance from the ocean (the pathway’s point of entry over land) and often increase, in a way that is quantitatively consistent with the biotic pump theory. A few pathways behaved differently, and Poveda et al. (2014) attributed those results to topographic effects. Poveda et al. (2014, p. 115) conclude that

> *"our results validate the biotic pump theory if tested in the proper settings of forests over flat terrains."*

Also Nobre (2014, p. 17) considered the results by Poveda et al. (2014) as validating the biotic pump theory. Poveda et al. (2014, p. 115) further offer the following commentary:

> *"The conventional wisdom states that the distribution of South American rainfall […] could be explained by a combination of precipitation recycling and mesoscale circulations driven by land surface heterogeneities. Nevertheless, it was not our aim to investigate the physical mechanisms explaining the space-time distribution of rainfall in tropical South America. Our study aimed at submitting the BiPAM [biotic pump] theory to an observational test, as a contribution in the line of reasoning put forward by the Editor's comment at the end of the study of Makarieva et al. [2013b], but also in the line of conclusions of Jasechko et al. [2013] that terrestrial water fluxes are dominated by biological fluxes (transpiration) rather than physical fluxes (evaporation), and that vegetation activity leads and increases water vapor at continental scales [Jiang and Liang, 2013]. Our results ratify the need for a stronger integration between hydrology, climatology, ecology, atmospheric, and plant sciences to further advance the earth system science."*

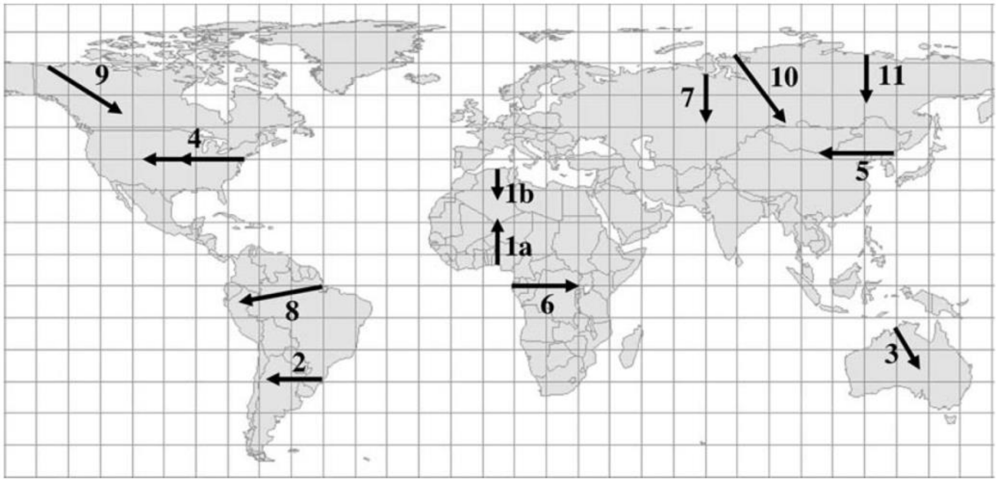


Figure 13. Geography of the regions where the dependence of precipitation P on distance x from the ocean was studied. Arrows start at x=0 and end at $x=x_{max}$. This figure is reproduced from Makarieva et al. (2009).

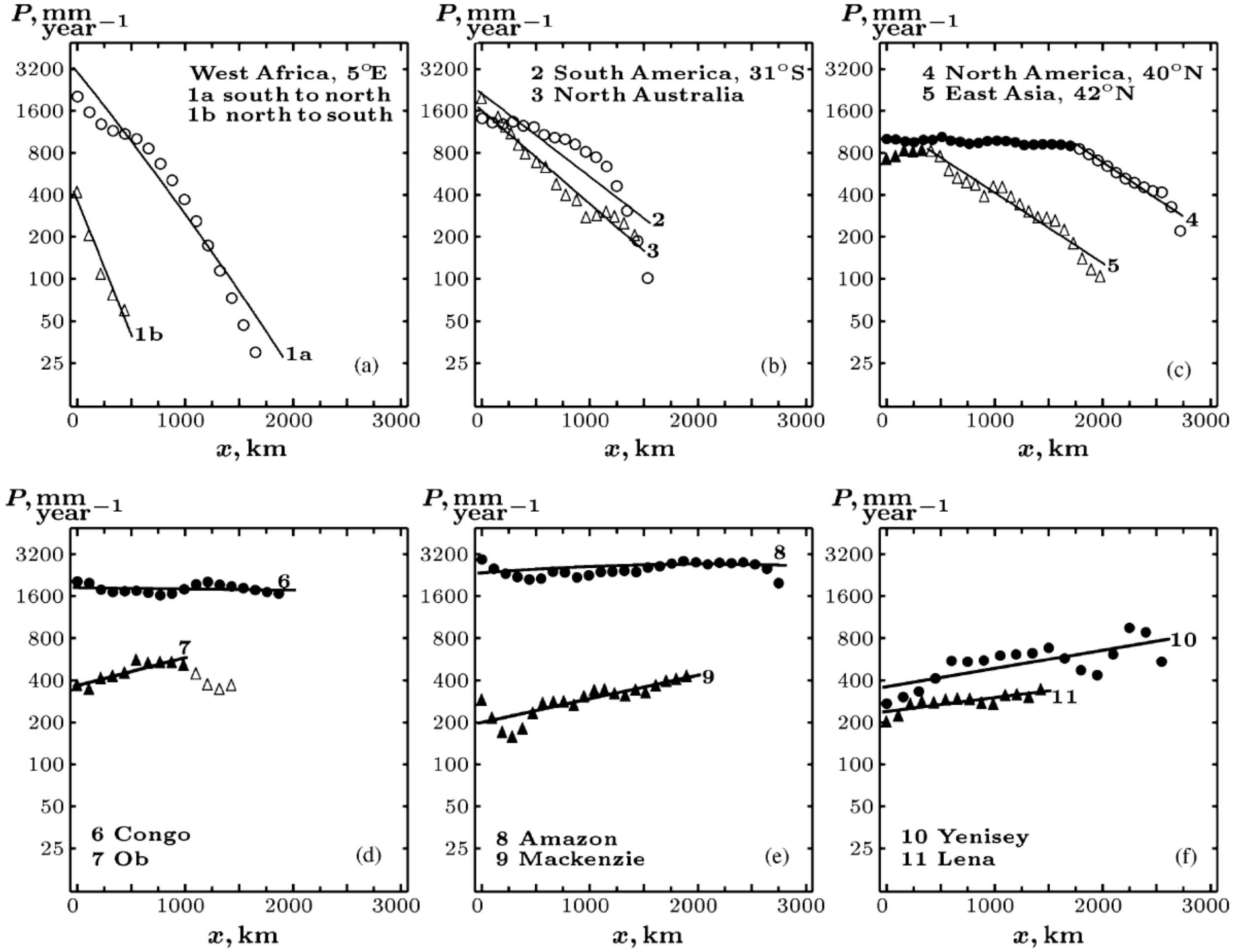


Figure 14. Dependence of annual precipitation P (mm year^{-1}) on distance x (km) from the ocean over non-forested territories (open symbols) and forest-covered territories (closed symbols). Regions are numbered as in Figure 13. This figure is reproduced from Makarieva et al. (2009).

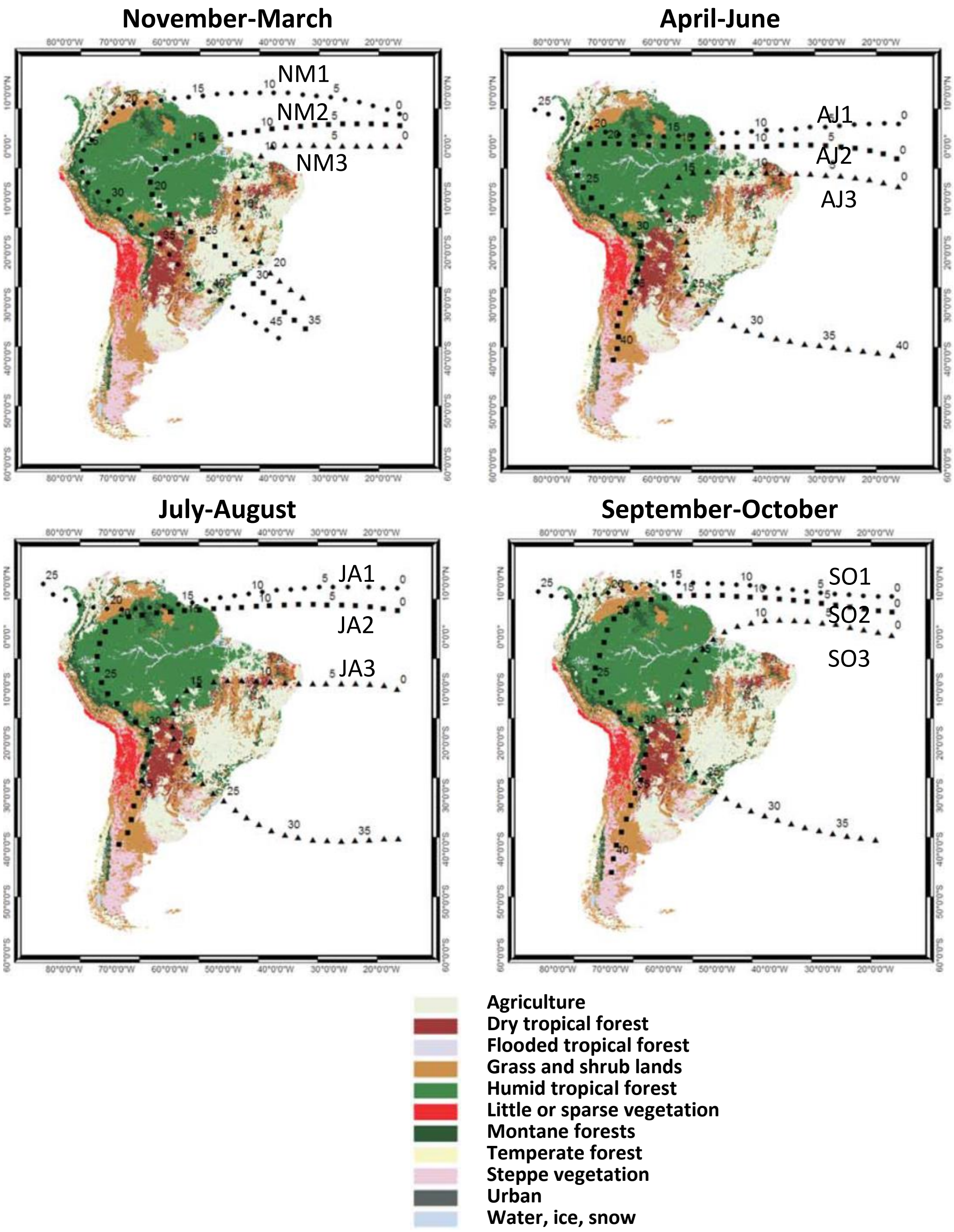


Figure 15. **Pathways of atmospheric rivers at different times of year superimposed on the land cover map of South America of Eva et al. (2004). This figure is adapted from Poveda et al. (2014) figures 10-13.**

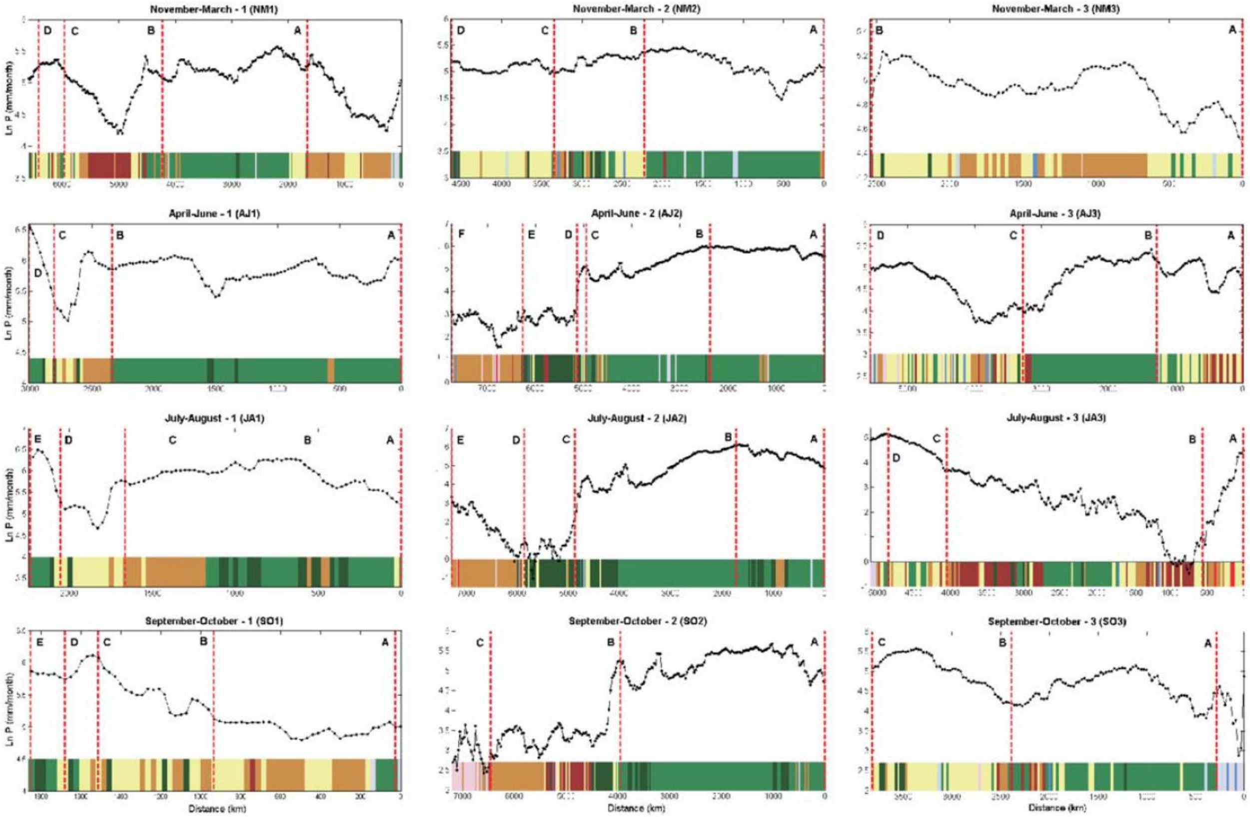


Figure 16. **Precipitation rates (y axis) plotted against distance (x axis) for each atmospheric river pathway shown in the previous figure. The colors at the bottom of each panel show the corresponding land cover (see the legend of the previous figure). The TRMM satellite precipitation dataset is used. This figure is reproduced from Poveda et al. (2014).**

2.6 Forests and dry season precipitation and duration

In Table 2, we reviewed evapotranspiration measurements obtained by the LBA project, showing that evergreen tropical forests, tropical semideciduous forests, and floodplain cerrado, all exhibit their highest evapotranspiration rates in the dry season – an eco-physiologic response particular to forests and permitted by the trees' deep roots. This high evapotranspiration during the dry season, provides much needed moisture to regions downwind from the forests (mechanism I), tends to enhance precipitation locally (via mechanism II), and directs moist oceanic air inland (via mechanism III). When exceptionally dry conditions occur, as in the 2005 and 2010 dry seasons, damage incurred by forest's biomass and canopy structure can last over a period of five or more years, during which the forest experiences diminished ability to set mechanisms I, II, and III in action during the dry season. The implication is that dry season droughts more easily become more severe in the years that follow.

Some researchers have suggested the forests' greening response to dry season conditions is an indication of their resilience to droughts. Evidence for such resilience appears to be, however, lacking. To the contrary, we have seen Brazil's forests suffer considerable losses during the severe drought years of 2005 and 2010. When in 2005 the southwest section of the Amazon was hit by an extreme drought, this was viewed by the scientific community as a rare opportunity to investigate the forest's response, and 13 reports were published in a special issue of *The New Phytologist* published in 2010, which we briefly review. In spatial extent, the 2005 drought was mostly restricted to the southwestern Amazon, and was especially severe in the dry season. In those two respects, the 2005 drought set itself apart from the droughts occasionally caused by warm phases of the El Niño – Southern Oscillation (ENSO) phenomenon, which affect the central and eastern regions the most and impact the wet season (Marengo, 2008). It is thought that warming of the tropical North Atlantic sea surface was a major contributing factor in the 2005 drought (Marengo et al., 2008; Zeng et al., 2008; Davidson et al., 2012).

Researchers issued reports of loss of biomass in the affected areas (with a concomitant loss of an estimated 1.6 gigatonnes of carbon storage[1]), due to slower tree growth and increased deaths (Phillips et al., 2009) – although a subsequent report attributed many tree deaths to thunderstorms (Negrón-Juárez et al., 2010) – decreased vegetation moisture content (Anderson et al., 2010) and a larger number of wildfires (Aragão et al., 2007). The 2005 loss of biomass agreed with the results from the deliberate drought experiments that had been running in the Amazon (Costa et al., 2010). In these experiments, half of the rainfall was consistently siphoned off for 7 years from a one-hectare plot of forest, resulting in a 30% decline in tree growth rates and a doubling of the tree death rate.

Drought struck the Amazon again in 2010, and this time it was spatially more widespread than the 2005 drought, affecting more than half the area of the Amazon, and resulting in the lowest stream flow discharge ever recorded at Manaus (Lewis et al., 2011; Xu et al., 2011). Based on satellite data collected during the new drought in 2010, Xu et al. (2011a) concluded there had been a decline in leaf area over

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[1] The Amazon River basin's biomass holds an estimated 100 billion tonnes of carbon (Malhi et al., 2006; Saatchi et al., 2007), which corresponds to more than 10 years' worth of global fossil-fuel emissions (Davidson et al., 2012)

the Amazon. During the 2005 drought, there was considerable confusion: Two different investigations based on the same data from the MODIS satellite yielded opposite conclusions concerning an increase or a decrease in leaf area over the Amazon during the 2005 drought (Saleska et al., 2007; Samanta et al., 2010 and 2011), a situation that according to Asner and Alencar (2010) reflects deficiencies in outdated satellite technology that requires replacement. The technical issues that make remote sensing of leaf area index challenging in the Amazon were described by Samanta et al. (2012).

It is believed that the 2005 and 2010 droughts are not isolated incidents, but the culmination of generally drier conditions observed from about 1970 to present (Marengo J. A. et al., 2008 and 2011; Xu et al., 2011; Li et al., 2008; Malhi et al., 2009). Wang et al. (2011) suggested that vegetation dynamics gives rise to persistence of precipitation anomalies across multi-year periods. It had previously been shown in modeling studies that in dry zones of the globe, and especially in zones of transition between wet and dry climates (i.e., semi-arid regions), feedback from vegetation contributes to perpetuating precipitation anomalies and enhances low-frequency (i.e., multi-year) variability of rainfall (e.g., Zeng et al., 1999; Wang and Eltahir, 2000a; Wang et al., 2004; Delire et al., 2004 and 2011). This is possible due to the strong coupling in those regions between soil moisture and precipitation (Koster et al., 2006).

Wang et al. (2011) showed that, because the Amazon forest is also strongly coupled with the atmosphere, particularly during the dry season, a strong feedback is sent from the vegetation to precipitation, generating a tendency towards multi-year persistence in precipitation anomalies. Saatchi et al. (2013) documented the persistence of canopy damage following the 2005 drought. The dependence of vegetation growth (net primary production, or NPP) on dry season soil moisture conditions modeled by Wang et al. (2011) is shown in Figure 17.

Figure 18, reproduced from Wang et al. (2011), maps the fraction of the total observed variance in precipitation over north and central South America reflects differences between multi-year periods. Throughout north and central South America, more than 30% of the total variance of precipitation is associated with periods of 5 or more years. In many sub-regions, colored in orange in the top panel of Figure 18, over 50% of the variance is associated with periods of 5 or more years (Figure 18, top panel); and in roughly those same sub-regions more than 30% of variance is associated with periods of 10 or more years (Figure 18, bottom panel). Using a global climate model with detailed land surface-atmosphere interactions (CAM3-CLM3-DGVM), Wang et al. (2011) show that this type of multi-year persistence of precipitation anomalies (“low frequency variability”) is only obtained when dynamic vegetation responses to precipitation are allowed in the model. When the model runs represented vegetation as unchanging, i.e., not responding in their lushness (in terms of density, leaf area index, etc.) to precipitation, no such low frequency variability of precipitation can be modeled.

Wang et al. (2011) conclude that *“Due to the damping effects of vegetation, the several years following a severe drought in a region may be more prone to recurrent droughts, making it more likely for drought years to occur as a cluster. A similar statement holds for flood years. In the Amazon region, the past decade witnessed two extreme droughts, one in 2005 and a much more severe one in 2010 that coincided with the local dry season [e.g., Marengo et al., 2008, 2011; Lewis et al., 2011; Xu et al., 2011]. The drought in 2010, a “once-in-a-century” event, caused substantial reduction of vegetation greenness* *across the Amazon basin south of the equator that did not recover when the rainy season precipitation returned to normal [Xu et al., 2011]. Results from our study suggests that, in absence of extremely strong oceanic forcing favoring precipitation in this region, many areas of Amazon will be prone to recurrent droughts in the several years following the 2010 drought."*

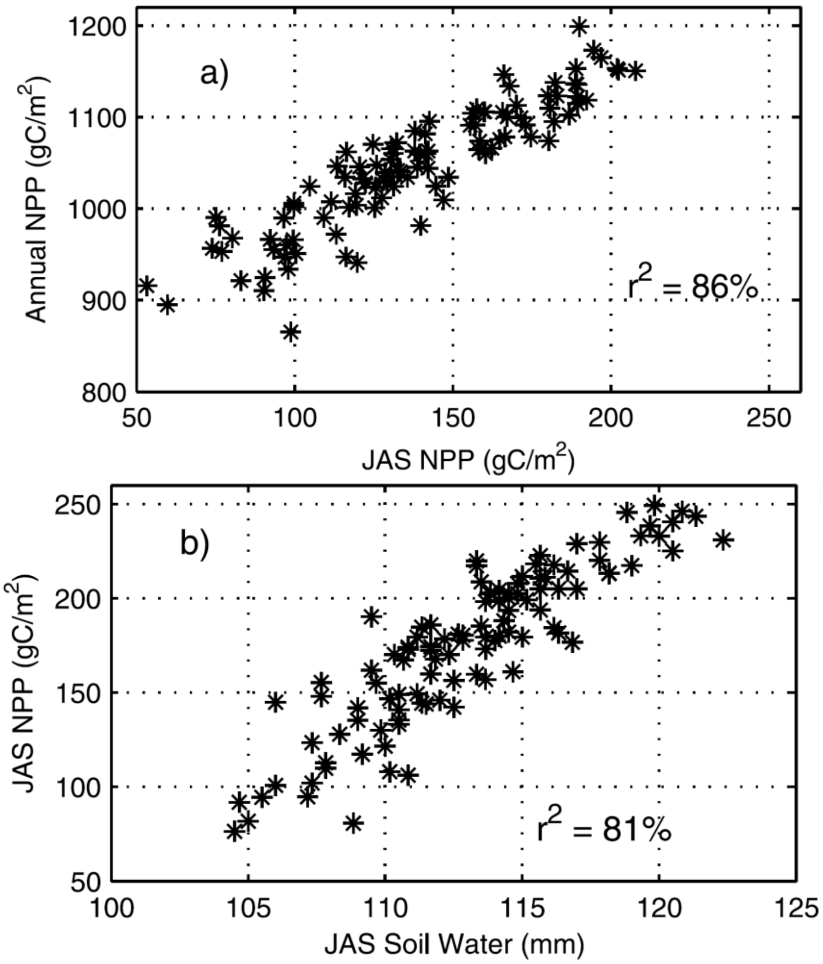
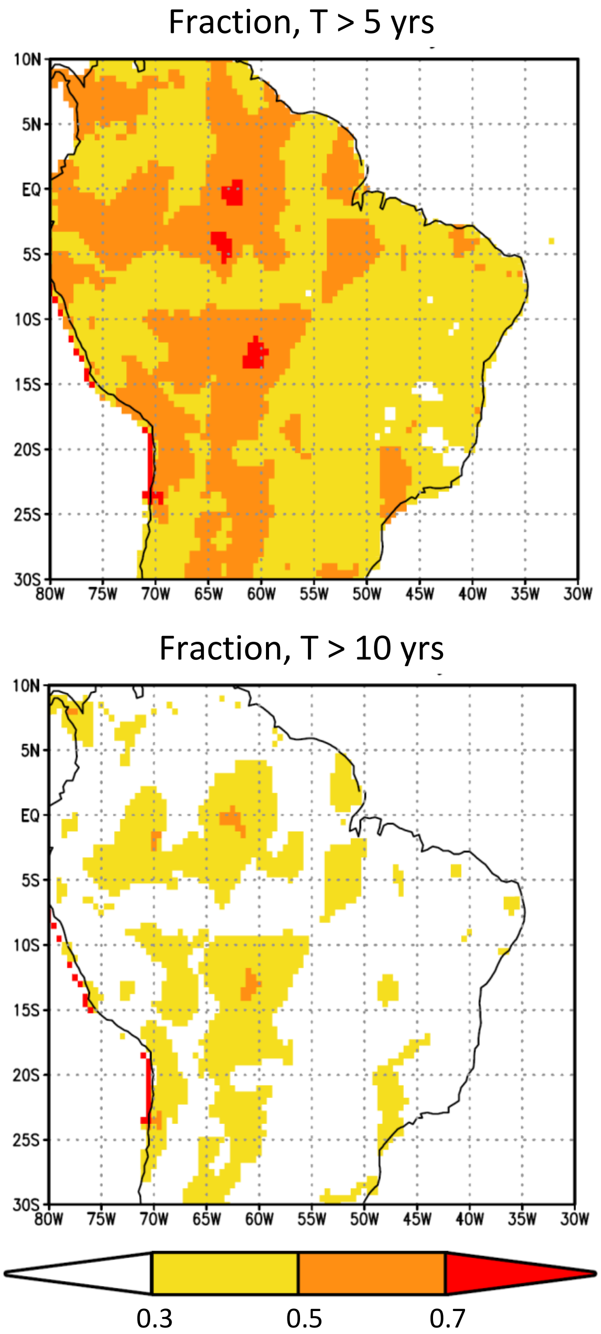


Figure 17. (a) Dependence of annual NPP [net primary production] on the dry season (July-August-September) NPP. (b) Dependence of dry season NPP on soil water in the top five soil layers (summed up to ~30 cm). NPP and soil moisture are both averaged over the region (60-70°W, 0-10°S).


Fraction, T > 5 yrs

Fraction, T > 10 yrs

Figure 18. **Fraction of precipitation variance with time scale longer than (top) 5 years and (bottom) 10 years, based on CRU precipitation data [Climatic Research Unit of the U. East Anglia, UK] over land during the period 1901-2006. This figure and caption are reproduced from Wang et al. (2011).**

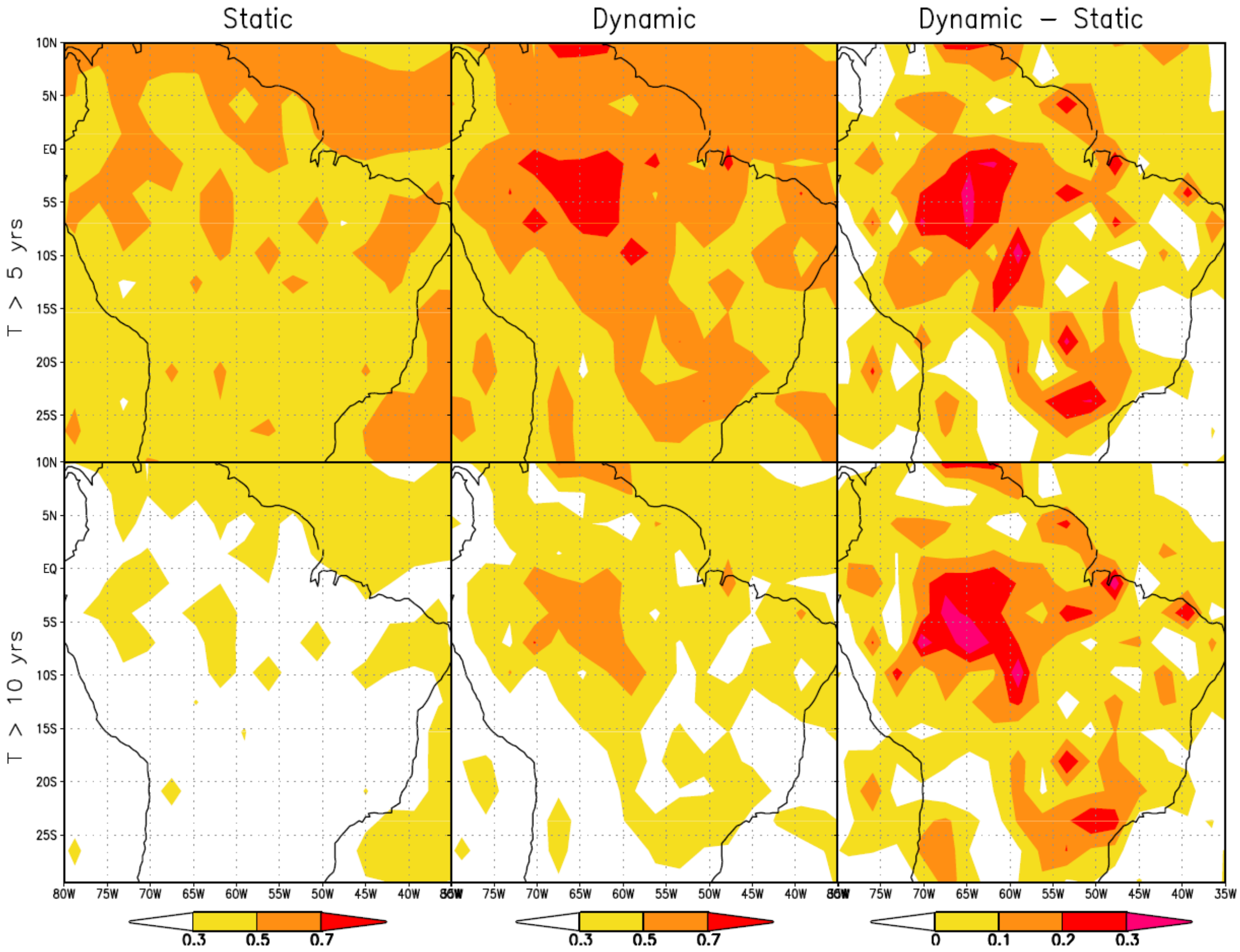


Figure 19. Fraction of precipitation variance with time scale longer than (top) 5 years and (bottom) 10 years simulated by CAM3-CLM3-DGVM (left) with static vegetation and (middle) with dynamic vegetation during 1901-2008, and (right) the difference between the two. This figure and caption are reproduced from Wang et al. (2011).

Davidson et al. (2012) provide a framework for understanding the linkages between natural variability, drivers of change, responses, and feedbacks in the Amazon basin. The following excerpts are quoted from Davidson et al. (2012):

> *"The IPCC fourth assessment climate change model runs show the highest probability of significant precipitation decrease predicted for southeastern Amazonia, where deforestation is greatest and where the climate and ecosystems transition from short-dry-season rainforest to long-dry season savannah ecosystems [Malhi et al., 2009; Rammig et al., 2010]. Various global and regional climate modelling approaches have suggested that once deforestation exceeds about 40% of the entire Amazon basin, a 'tipping point' might be passed [Nobre and Borma, 2009], whereby decreased energy and moisture released to the atmosphere from the largely*

deforested landscape would result in reduced convection and precipitation, and a shift in the forest–savannah boundary or large-scale dieback of rainforest.

A number of deficiencies in the structure and application of global climate models suggest that the uncertainty of these simulated outcomes and estimated tipping points is very high. A few examples include: (1) many of the models simulate too little precipitation in the Amazon owing to incomplete representation of the role of the Andes in continental circulation and large-scale convection over the core of the western Amazon, and also owing to coarse representation of the land surface with respect to small-scale meteorological processes [Malhi et al., 2009]; (2) inter-annual variation of sea surface temperatures in the tropical Pacific and tropical north Atlantic Ocean are closely associated with extreme flood and drought events in the Amazon [Marengo, 2004; Marengo et al., 2008; Lewis et al., 2011], but these teleconnections to the Amazon are not yet adequately represented in global climate models; and (3) the biophysical response of vegetation to increasing atmospheric CO_2, including effects on evapotranspiration, may be one of the largest unknowns for the future of the Amazon forests. The probability of simulated forest dieback due to decreased rainfall is greatly reduced when a strong CO2 fertilization response is included in a vegetation model [Rammig et al., 2010], but the scale of the actual impact of increasing CO_2 on photosynthetic efficiency remains a large source of uncertainty.

"In summary, the changes in precipitation and discharge associated with deforestation already observed in the southern and eastern Amazon demonstrate a potential for significant vegetation shifts and further feedbacks to climate and discharge. Numerical models strongly suggest that potential future deforestation may also cause feedbacks to large-scale climate and vegetation distribution, but the models have deficiencies that prevent confident prediction of the magnitude or spatial distribution of deforestation that would lead to a significant region-wide decrease in precipitation—including whether a threshold, or tipping point, exists whereby the basin could slip into a dry, stable state. Focusing on a theoretical and difficult-to-define tipping point for the entire basin may divert the scientific community from the important large-scale regional changes that are already taking place, such as lengthening of the dry season [Butt et al., 2011; Knox et al., 2011] and increases in river discharge [Costa et al., 2003; Coe et al., 2011] in ecologically and agriculturally important transition zones of the eastern and southern flanks of the basin."

3 HOW DO CHANGES IN LAND COVER AFFECT STREAM FLOWS AND GROUND WATER?

3.1 Effects of afforestation on stream flows and ground water across scales

3.1.1 Catchment monitoring studies and modeling studies

Catchment studies with the aim of investigating the effects of different land covers on local hydrologic variables represented an important component of the Large-Scale Biosphere-Atmosphere Experiment (LBA) family of projects. A summary of results was presented by Tomasella et al. (2009) and Table 3 is reproduced (redrawn) from their publication. The results for small catchments provide evidence that forested and non-forested catchments have different runoff ratios. Such effects are either not present or are difficult to detect in larger catchments (e.g., Bruijnzeel, 2004).

Tomasella et al. (2009) emphasized the dependency of hydrologic observations on the size of the catchment, and presented two illustrative figures, reproduced here in Figure 20 and Figure 21. They offer the following interpretations:

> *"Disregarding a vast list of factors such as interannual variability, differences in the geology, landscape form, effect of different land use changes on the soil conductivity, and periods of analysis,* [Figure 20] *seems to indicate that the differences in response of a small catchment varies as a function of the area."*

And:

> *"*[Figure 21] *presents the proportion of base flow to total rainfall as a function of drainage area. Because of the geomorphological characteristic of the dissected Amazonian valleys, the increase of scale is associated with an increase in the relative contribution of the valley/riparian area (Hodnett et al., submitted manuscript, 2008), which is the most important area for stormflow generation. This explains why there is an increase of stormflow contribution with area, both in forested and deforested catchments. Because of the compaction of soils, particularly in heavily grazed areas, Hortonian overland flow is more likely to occur in areas of low infiltration (Zimmermman et al., 2006), which explains the differences between forested and deforested areas."*

The following is the analysis and interpretation of the catchment studies data offered by Tomasella et al. (2009):

> *"Costa et al. (2003) detected an increased discharge in the Rio Tocantins (400,812 km2), which was attributed to the deforestation in its headwater, an area originally covered [by] cerrado*

> *(savannah type vegetation) but converted to pasture and agriculture. On the other hand, Trancoso (2006) showed that the trends detected in selected stations (with at least 25 years of data) on the Xingu (483,397 km2), Tapajós (486, 367 km2), and Madeira (3,354,222 km2) rivers can be explained by changes in the same direction of rainfall. This correlation indicates that those changes are not related to a reduced evaporation due to forest conversion (the sources of those rivers are in the severely disturbed area of Amazonia known as the deforestation arc). Perhaps the most significant result is observed in the Ji-Paraná Basin […] (Linhares, 2005), which is one of the most impacted mesoscale basins in Amazonia (60% of its original vegetation has been removed), where no trends either in rainfall or streamflow can be detected.*
>
> *"Unlike small catchments, large basins have a variety of land use types associated with intense temporal changes. In Amazonia, specifically along the deforestation arc, the remaining forest is confined to an increasingly fragmented area of secondary forests, abandoned agricultural land, and primary remnants (Laurance and Bierregaard, 1997). As shown by Giambelluca et al. (2003), the magnitude and spatial pattern of transpiration in forest patches is strongly influenced by the conditions in surrounding clearings. According to those authors, transpiration enhancement can occur not only at forest edges, but also well within the patch for trees whose canopies are exposed to advection. They concluded that 'fragmentation of remaining forested areas would partly offset the reduction in regional evaporation due to deforestation.' This is generally attributed to the input of sensible heat energy to the surrounding clearings and secondary younger vegetation. In addition, Hölscher et al. (1997) and Sommer et al. (2002) measured evaporation rates similar to those obtained in mature forests in 2- and 3.5-year-old secondary vegetation. Thus, the vigorous growth of secondary tropical [forests] can cause a rapid return of streamflow totals to predisturbance levels (Bruijnzeel, 2004).*
>
> *"Based on this evidence, a plausible explanation for the fact that the differences in the signal between forested and deforested basins cannot be detected at larger scales could be related to the aggregation of the evaporation processes in a fragmented landscape."*

In their interpretation above, Tomasella et al. (2009) consider only localized avenues by which land cover can affect rainfall, i.e., they consider only mechanism II (section 2.4). If we interpret the data in light of all three mechanisms, I, II, and III, we can then hypothesize that larger catchments experience different seasonal rainfall rates depending on land cover, and also depending on the land cover located along the atmospheric pathways upstream from it – as shown by the work of Spracklen et al. (2012), reviewed in section 2.3. This interpretation is also consistent with the findings of Trancoso (2006) cited by Tomasella et al. above. Indeed, Trancoso (2006) reached the conclusion that, over large catchments, precipitation increases with evapotranspiration, based on statistical analysis of observed runoff and precipitation time series, for Amazon catchments of differing degrees of remaining forest cover. An increase in precipitation over time due to deforestation would counteract a simultaneous rise in the runoff ratio of a large watershed.

More recent catchment studies include those of the PROMAB (Programa de Monitoramento Ambiental em Microbacias), a program developed by a partnership between IPEF (Instituto de Pesquisas e Estudos Florestais) and the Brasilian forestry sector. Results from PROMAB may allow identification of best management practices applicable to afforested areas (addressed below) (Lima et al., 2008), Lima (2010).

The study by Rodriguez et al. (2010) for the Ji-Paraná River basin considered nested sub-basins, ranging in size from 4,340 km2 (SB1) to 33,012 km2 (SB7) (Figure 22). The Rancho Grande paired watersheds study by Germer et al. (2010) compared two small basins approximately 400 meters apart, where one was covered by forest and the other by pasture. Of particular interest was a comparison between their stormflow hydrographs for a rainfall event on March 5-6, 2005 (Figure 23).

Table 3. Summary of results in LBA catchments in terms of the hydrologic response. This table is reproduced from Tomasella et al., 2009.

Basin	Area (km^2)	Location	Land Cover	Rainfall (mm a^{-1})	Total Discharge (mm a^{-1})	Runoff Coefficient (%)	Base Flow (%)	Source
Deforested								
Fazenda Vitória	0.0072	Easterm Amazônia	Pasture	1769	296	17.3		Moraes et al. [2006]
Cumaru WS3	0.122	Easterm Amazônia	Fallow Vegetation-Agriculture	2253	857	38.0	98.4	Wickel [2004], Wickel et al. [2008]
Cumaru WS1	0.358	Easterm Amazônia	Fallow Vegetation-Agriculture	2253	921	40.9	98.4	Wickel [2004], Wickel et al. [2008]
Colosso	1.22	Central Amazônia	Pasture	1602	689	43.0	73.4	Trancoso [2006]
Nossa Senhora	14.5	SW Amazônia	Pasture	1918	671-894	35.0-46.6	55.0-66.0	Biggs et al. [2006]
Rancho Grande	0.0073	SW Amazônia	Pasture	2184	378	17.3		Chaves et al. [2008]
Forested								
Juruena Oxisol	0.0095	Southerm Amazônia	Forest		1394		97.5	Johnson et al. [2006]
Juruena Ultisol	0.0194	Southerm Amazônia	Forest		1755		96.8	Johnson et al. [2006]
Fazenda Vitória	0.0033	Eastern Amazônia	Forest	1628	48	3.2		Moraes et al. [2006]
Asu Mirim	1.26	Central Amazônia	Forest	1582	329	21.0	84.8	Trancoso [2006]
Asu	6.56	Central Amazônia	Forest	2514	1071	42.6	40.0	Hodnett et al. [2008]
Rancho Grande	0.0137	SW Amazônia	Forest	2184	16.7	0.8		Chaves et al. [2008]

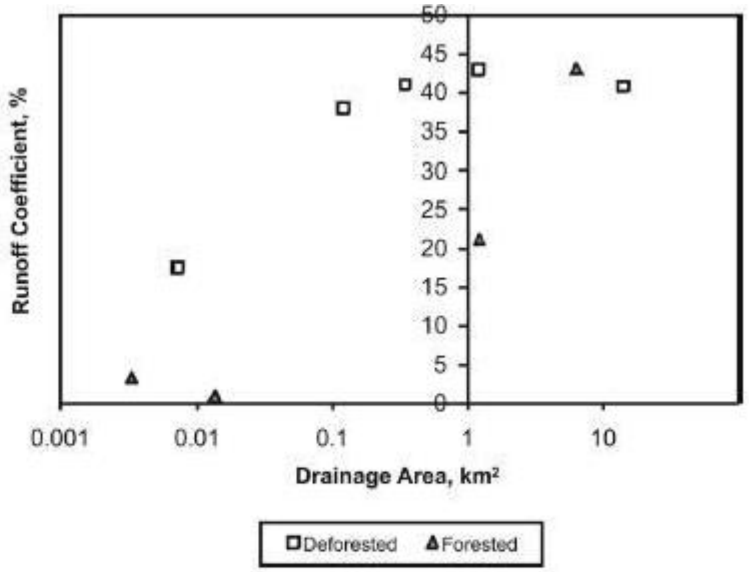


Figure 20. Summary of results in LBA catchments in terms of the hydrological response. This figure and caption are reproduced from Tomasella et al. (2009).

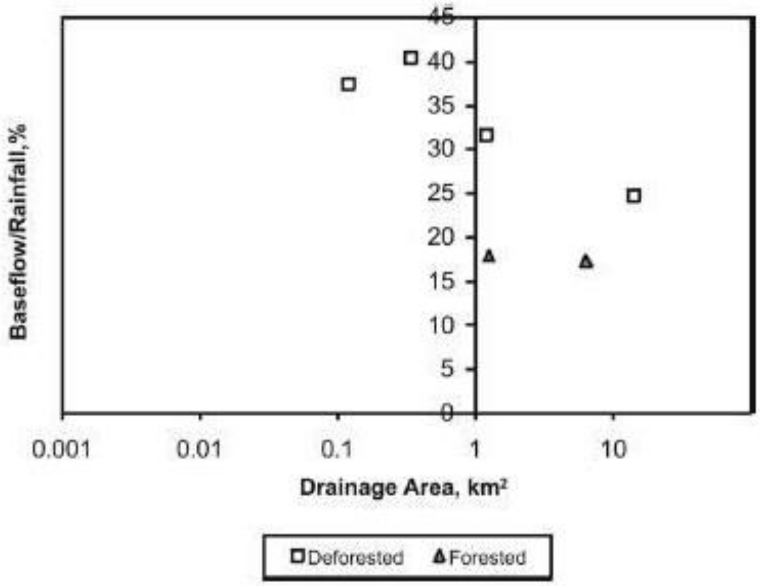


Figure 21. Percentage of base flow as a function of the drainage area in LBA catchments. This figure and caption are reproduced from Tomasella et al. (2009).

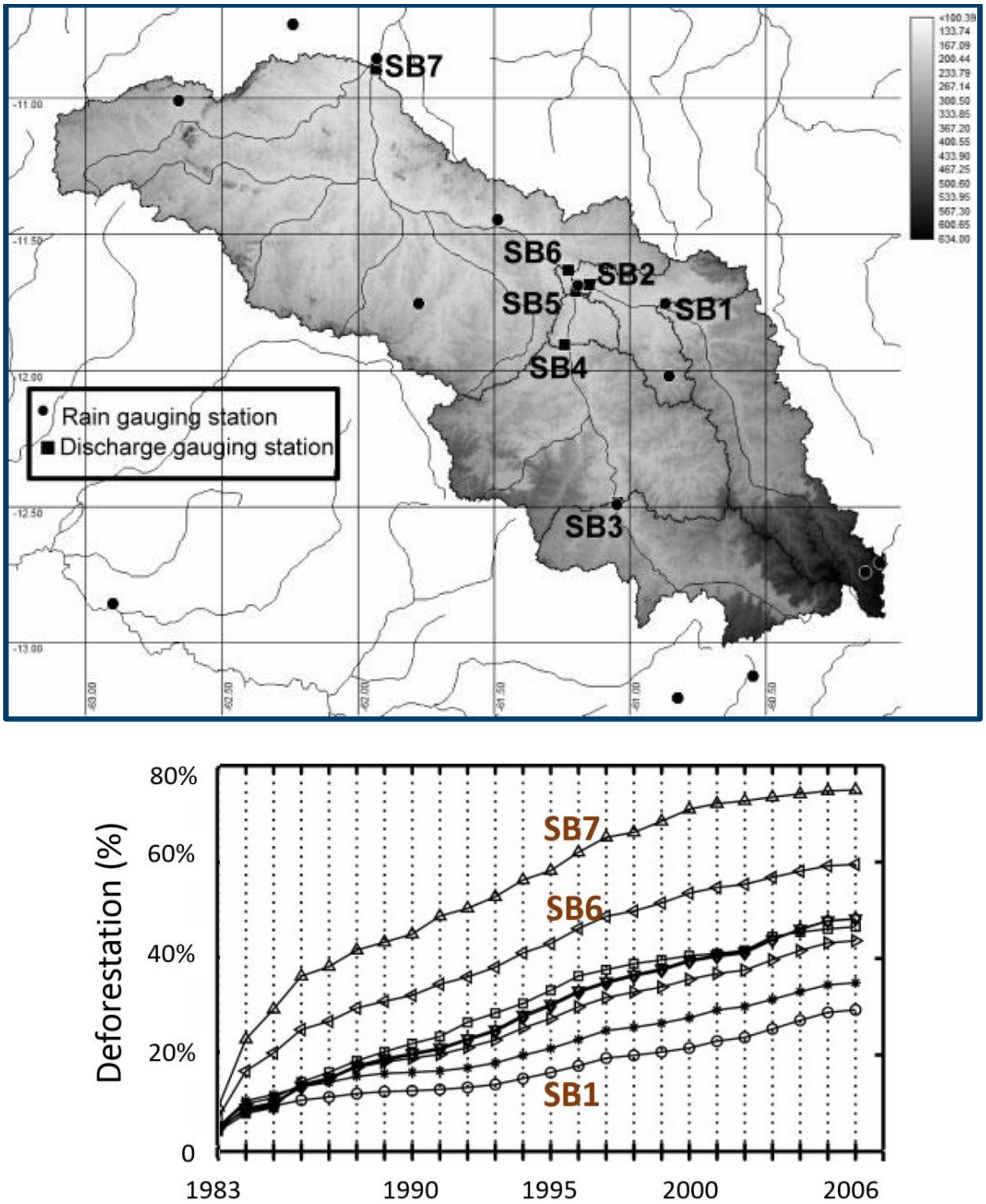


Figure 22. The Ji-Paraná study by Rodriguez et al. (2010) considered nested sub-basins, ranging in size from 4,340 km2 (SB1) to 33,012 km2 (SB7). The largest sub-basin (SB7) had the largest degree of deforestation, and the smallest sub-basin (SB1) had the smallest degree of deforestation (in percentage). Trends were detected in the streamflows of small sub-basins, but not larger ones, including increased peak discharges and decreased low flows. There was also a shortening of storm runoff lag times. These figure panels are reproduced from figure panels in Rodriguez et al. (2010).

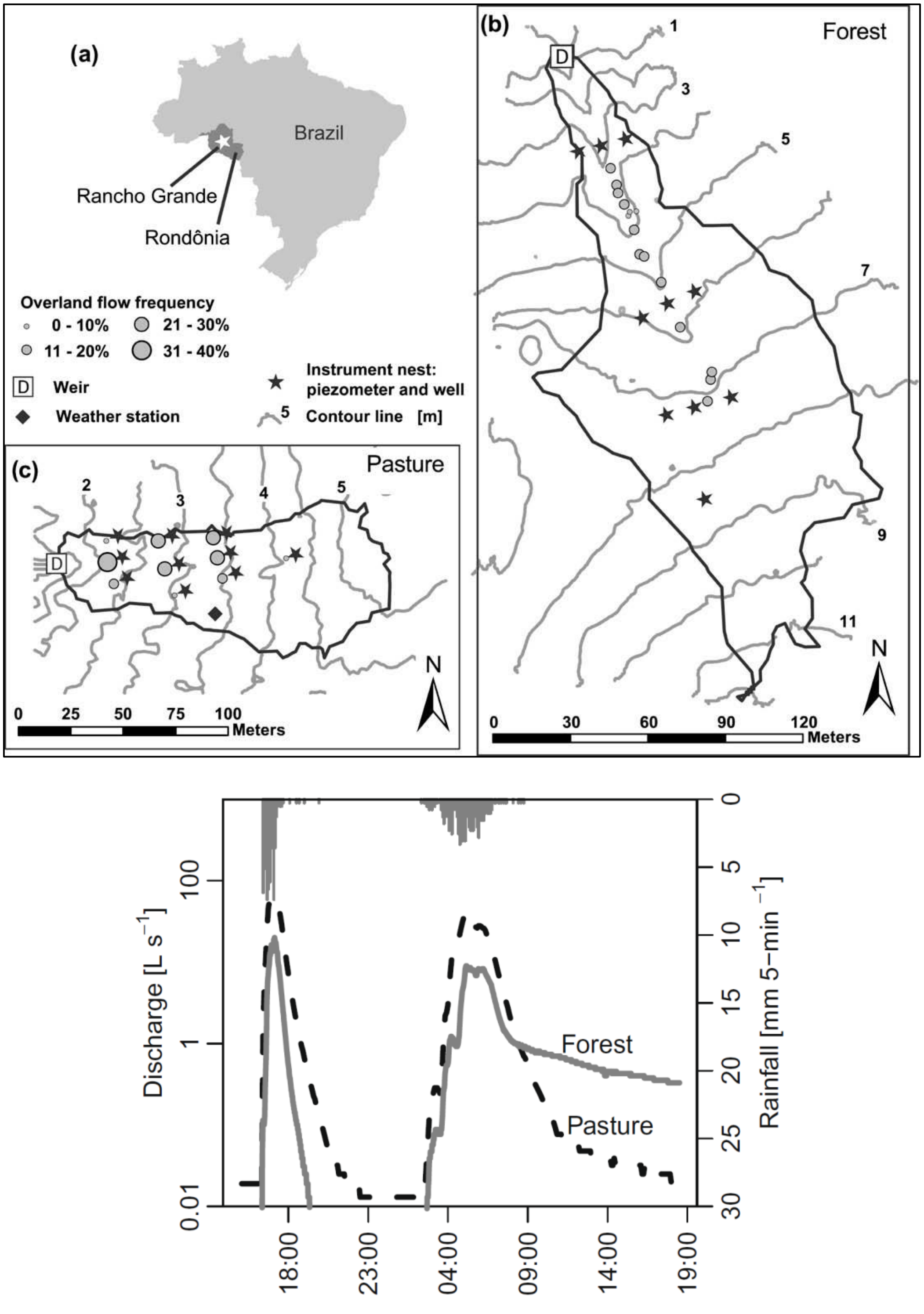


Figure 23. In the Rancho Grande paired watersheds study by Germer et al. (2010), the hydrologic response of two small basins, approximately 400 m apart, is compared for a rainfall event on March 5-6, 2005. Discharge is plotted on a logarithmic scale. These figure panels are reproduced from figure panels in Germer et al. (2010).

A few studies have addressed watersheds in the Cerrado biome, the second largest biome in Brazil, with 203 million hectares, or about 22% of Brazil's territory. This biome is one of the biologically most diverse regions in the world and one of 25 global biodiversity hotspots. It represents a vegetation mosaic of grasslands, forest composed of cerrado (savannah type vegetation) and dry and riparian gallery forest. There are two distinct seasons, a dry season from May to September, and a wet season from October to April. According to Klink and Machado (2005), deforestation rates in the Cerrado have been historically higher than in the Amazon biome, compared to which the Cerrado receives lower conservation efforts. Agriculture in the Cerrado is profitable and continues to expand and require road infrastructure. Fire is used often for land clearing (Klink and Machado, 2005).

Collischonn (2001) applied the MGB-IPH model ("Modelo de Grandes Bacias") to three large watersheds, one of them in the Cerrado biome: the Taquari River in Mato Grosso do Sul. The goals were to evaluate the hydrologic impacts of land cover changes, as well as climate variability. The model was also to be used for streamflow forecasting. Collischonn (2001) reported difficulty in estimating vegetation parameters for the model, which are central to simulation of evapotranspiration and the consequences of land cover changes. Thus, results were presented as preliminary. Alcântara (2009) tested the available time series of precipitation and stream flow in the watershed of "Alto e Médio Teles Pires", subject to marked recent land cover changes, but the short record length (1993-2006) did not allow definitive conclusions. Oliveira et al. (2013) used satellite-based estimates of precipitation (TRMM) and ground water storage (GRACE) over the Cerrado biome region in a first attempt at creating a course-scale water balance of the region.

Bayer (2014) applied the same hydrologic model as Collischonn (2001), the MGB-IPH, to the Paraná River basin, which lies partly in the Floresta Atlântica (Atlantic Forest) biome and partly in the Cerrado biome (Figure 24). The modeled streamflow decreased approximately linearly with increases in the vegetation parameters leaf area index (LAI) and average height (h), both of which favor higher evapotranspiration; and increased approximately linearly with albedo (α) and surface resistance (r_s), which limit evapotranspiration. The modeled streamflow showed increasing time trends as so did the observations. Low flows also increased, and to a lesser extent so did peak flows. Bayer (2014) attributed to changes in vegetation land cover a fraction of 39% of the observed long-term increase in streamflows, and 61% to precipitation increases. From examination of Figure 25 where we see a step-like change in the streamflow regime. No such sudden change in land cover is apparent from Figure 26. It appears that a climatic shift rather than a land cover change is likely to bear principal responsibility – although certainly we have seen in this literature review that land cover changes occurring elsewhere have the potential capacity to induce climatic changes (section 2).

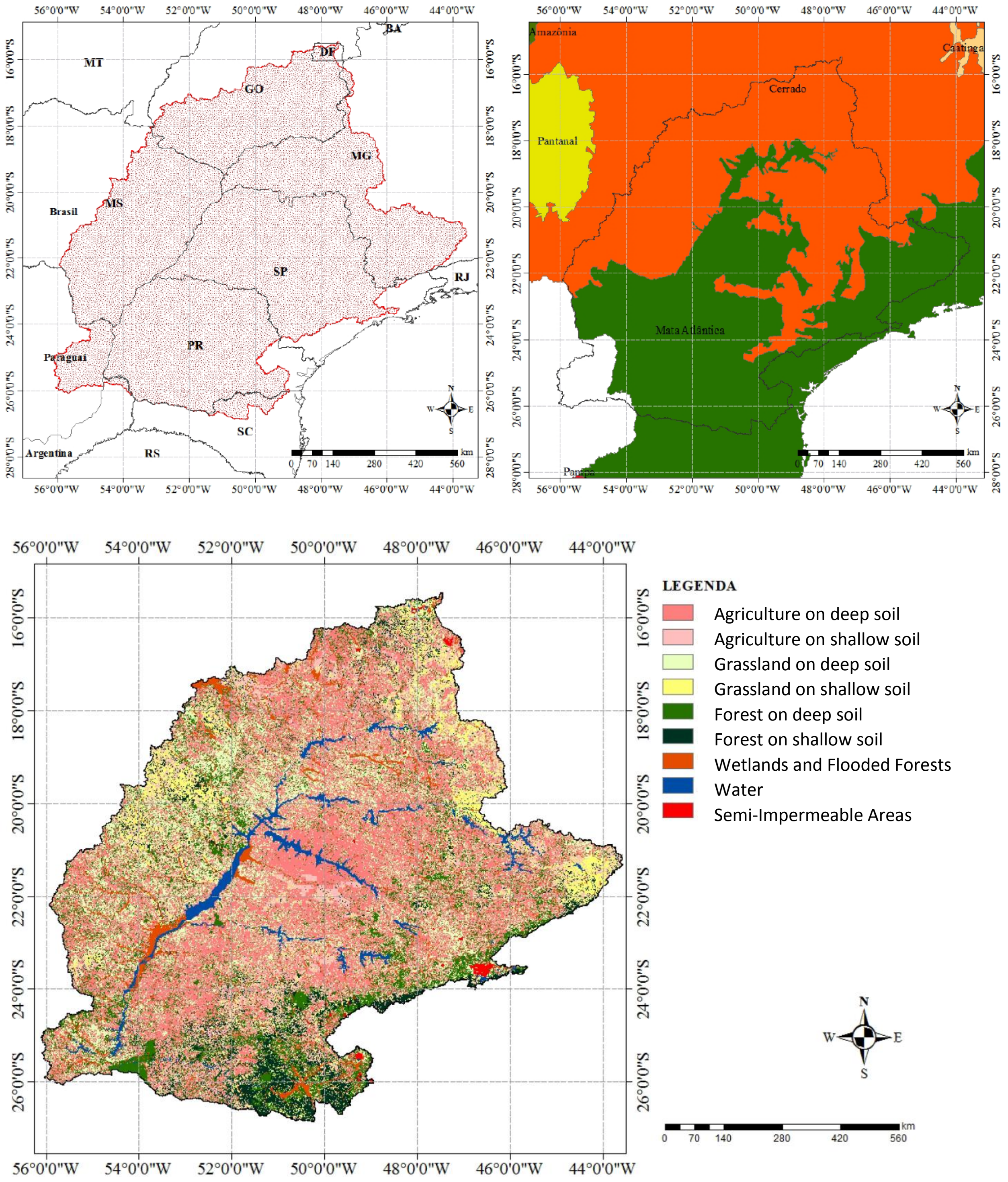


Figure 24. Location of the Paraná watershed (top panels) and representation of land cover (dataset from Eva et al., 2002) in the hydrologic model simulations by Bayer (2014). These figure panels are reproduced from Bayer (2014).

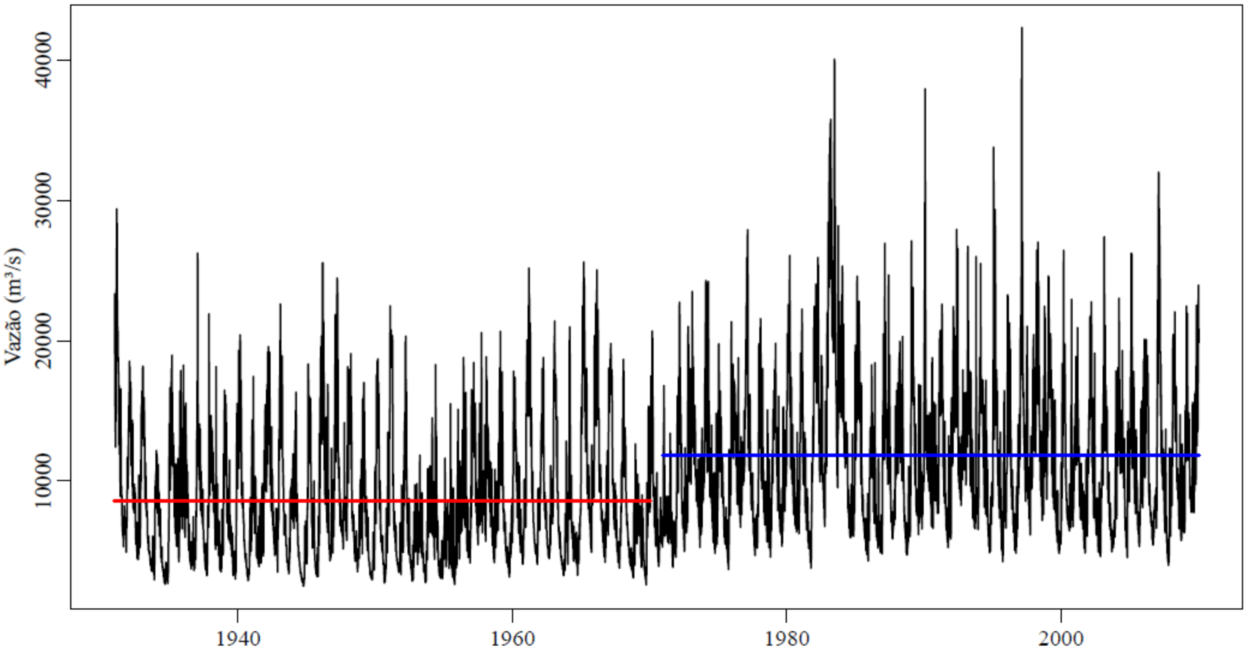


Figure 25. Naturalized daily stream flow rates (y axis) over time in the Paraná River basin at Itaipu. Period averages are shown in red for 1931-1970 and in blue for 1971-2010. There is an apparent step-like increase in the 1970s in streamflows, including baseflows and maximum flows. No sudden change in land cover was seen at this time in the figure that follows. This figure is reproduced from Bayer (2014).

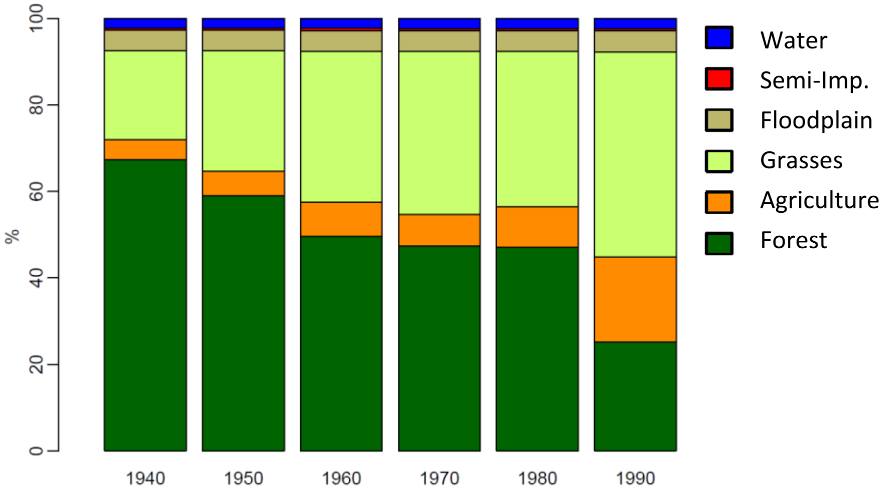


Figure 26. Land cover changes in the Paraná River basin, according to the data set by Leite et al. (2012). This figure is reproduced from Bayer (2014).

3.1.2 Afforestation of degraded areas

Few studies to date have addressed degraded areas. Instead, most studies of afforestation consider agricultural crops as the benchmark for comparison. Agricultural land and degraded land differ greatly, however, and represent markedly distinct benchmarks against which to evaluate the impacts of afforestation on water resources. The most significant difference is the poorer condition of soils in degraded areas compared to cropland areas.

Lal (1987) defined “degraded areas” as those where human-imposed land use has led to lack of diversity in vegetation species and structure, soil erosion, and soil compaction or crusting. Generally speaking, tropical soil has low fertility, and this renders it especially vulnerable to degradation (Grip *et al.*, 2005). The effects on soil generally result in diminished infiltration capacity, which in turn leads to increased infiltration-excess overland flow and higher contribution from surface versus subsurface flow paths to storm flows, resulting in reduced soil water recharge (e.g., Pereira, 1989; Sandström, 1998).

Afforestation of degraded areas can be spontaneous or planted. Spontaneous forest regrowth can occur on degraded areas, provided the topsoil is not excessively degraded and that tree seeds or seedlings are still present or arrive from nearby patches of natural forest (e.g., Bruijnzeel et al., 2005). Tree plantations often exhibit slower growth compared to spontaneous forest regrowth. Even for tree species that do grow rapidly when planted, such as acacias, pines and eucalypts, recovery of a structurally complex, multi-level canopy is slower than for spontaneous forest regrowth (Beadle, 1997; Hölscher et al., 2005).

Compared to short vegetation types – such as grass, scrub, and agricultural crops –, forests have greater canopy height, leaf area and aerodynamic roughness, as well as lower albedo and deeper roots. These physiological distinctions influence interception, local hydrologic flow paths, and evapo-transpiration. Their lower albedo enables forests to absorb about 5-10% more solar radiation than shorter vegetation. The deeper roots permit access to ground water and continued transpiration during the dry season (e.g., Roberts et al., 2005).

For the increase in interception rates associated with afforestation, Scott et al. (2005) – citing Bruijnzeel (1989a) and Bruijnzeel and Proctor (1995) and the data review by Bruijnzeel (1997) – offers values in the range 10-20% as typical for most lowland situations, and 20-35% for most montane forests. The specific value within these ranges is determined by tree species (Scott et al., 2005), with eucalyptus on the low end of the range (about 12%), broad-leaved hardwood species such as teak and mahogany in the middle of the range (about 20%), conifers (such as pines, *Araucaria* and *Cupressus*) in the upper-middle range (20-25%), and *Acacia mangium* in the upper end of the range (20-40%).

Thus, at least on the relatively short term, afforestation of degraded areas can be expected to lead to soil moisture and ground water declines and lower water yields in the local catchment (e.g., Hamilton and King, 1983; Bruijnzeel, 1990). On the longer term, requiring several decades time, restoration of soil infiltration capacity, topsoil bulk density, soil depth, and surface detention and retention storage as a result of afforestation are possible and have been documented by observation (e.g., Scott *et al.*, 2005; Bruijnzeel, 2005). Improvements of baseflow do not necessarily result from the higher infiltration capacity because of higher evapotranspiration in the afforested areas (e.g., Bruijnzeel, 1989). However, such improvements in baseflow are more likely under severely disturbed surface conditions (cf. Table 4 in Scott *et al*., 2005).

For either spontaneous forest regrowth or tree plantations on formerly degraded scrubland, abandoned agricultural fields, or grassland, the usual effect is a progressive decrease of the local catchment's water yield over 5-10 years, stabilizing at levels similar to the original old-growth forest (Grip et al., 2005). If there is significant advection of heat from surrounding cleared areas, water use in the new forest patch may surpass that of the original old growth forest (Hölscher et al., 2005).

The decline in water yield may be particularly rapid in the first 5 years for the fastest growing species (such as acacias, pines and eucalypts) and for cases where the topsoil had suffered the least degradation, but is less rapid in the case of tree plantations compared to spontaneous regrowth (e.g., Bruijnzeel et al., 2005).

The effect of vegetation cover on peak and volume of storm flows is determined by how large the storage capacity it generates is relative to the total storage capacity of the catchment, and how large the rainstorm is (Scott et al., 2005). Under most storm conditions, larger peak and volume of storm flows are expected from degraded areas compared to afforested areas; while under conditions of extreme rainfall and soil wetness, large storm flows may be produced from forested areas as well (Scott et al., 2005; Hewlett, 1982; Hamilton and King, 1983; Bruijnzeel and Bremmer, 1989; Bonell, 2005).

In conclusion, as an alternative to degraded areas, afforestation may generally be capable of restoring soil hydrological function in those areas, through improvements in soil infiltration, topsoil bulk density, soil depth and surface detention and retention storage (Figure 27). However, observational evidence specific to degraded areas is lacking, and soil restoration can be expected to take several decades.

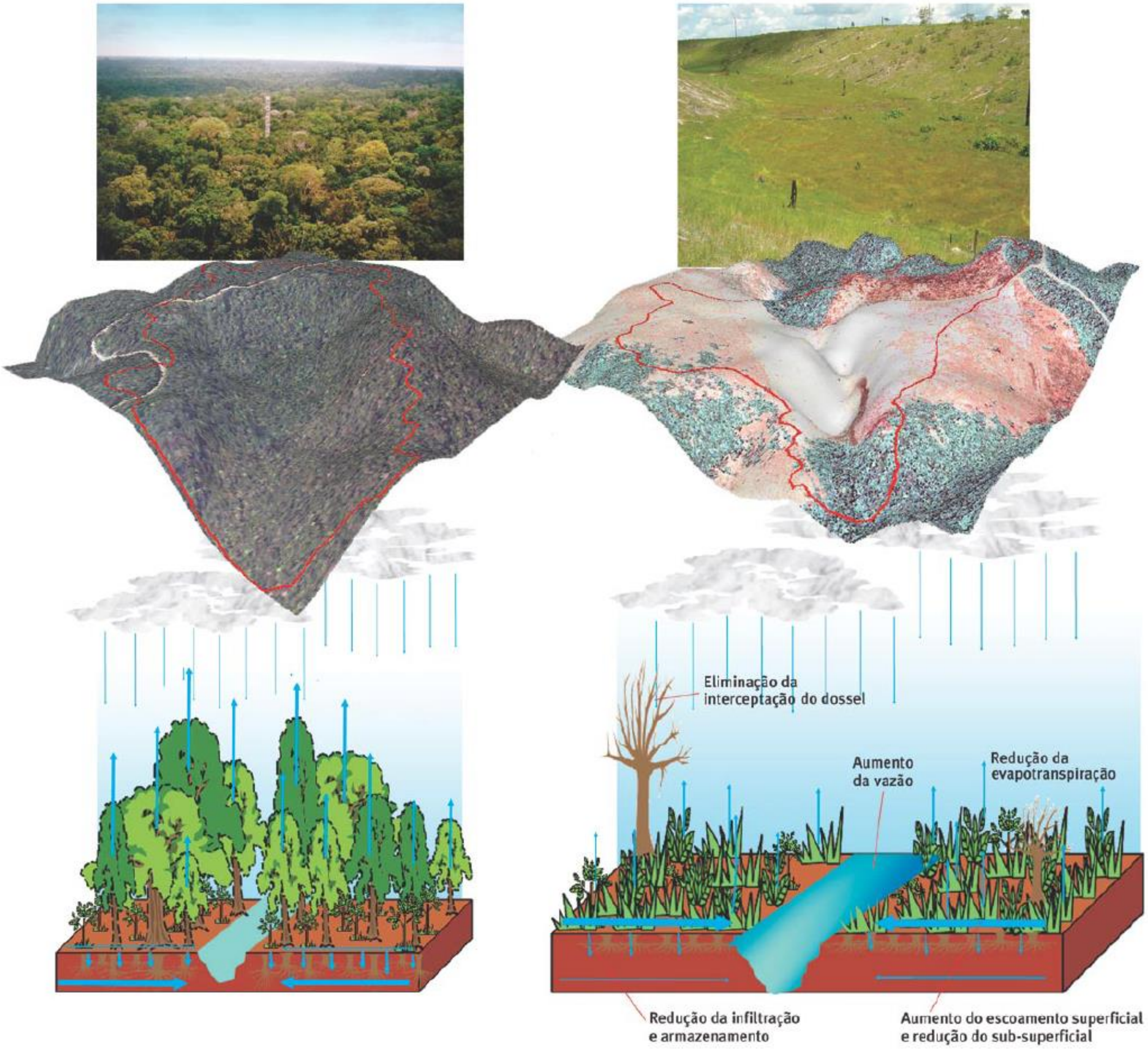


Figure 27. **Experimental catchments with forest cover versus pasture: differences in hydrologic behavior. The text labels in the bottom right panel read "Elimination of canopy interception", "Reduction of evapotranspiration", "Reduction of infiltration and storage", "Increase in surface runoff and decrease of sub-surface runoff", and "Increased streamflow". This figure is reproduced from Trancoso et al. (2007).**

3.2 Management strategies for protecting local stream flow after afforestation of degraded areas

3.2.1 Considering the local water resources system

The impacts of small-scale afforestation upon a water resources system depends on whether the system is served by a reservoir. If there is no reservoir, there may be concern that the afforestation will lead to diminished flows during the seasonal low-flow periods, with implications to water quality and ecosystems. Indeed there is evidence of such low-flow declines associated with afforestation, often proportionately greater than the declines in mean annual streamflow – as reviewed by Brown et al. (2007) and Dye and Versfeld (2007) –, although van Dijk et al. (2007) showed that probable bias in experimental catchments confounds this interpretation.

If there is a reservoir, it may be able to transfer flows from the wet to the dry season, so as to compensate for a decline in seasonal low flows. The capacity to do so will depend on the relative magnitude of the low-flow decline to the reservoir's storage capacity, and on water demands in the different seasons. If the reservoir's releases serve users located at considerable distance downstream, there will generally be many water losses along the way, which may be losses to riparian zones and floodplains, to groundwater, weirs, irrigation supply channels, etc (van Dijk and Keenan, 2007). Thus, a reduction in inflow to such a reservoir as may result from afforestation will in general translate into a smaller volume loss to the downstream users. Such effects have been exemplified using hydrologic modeling (Brown et al., 2007).

3.2.2 Management strategies for afforested areas

At locations where there is a goal to minimize evapotranspiration from afforested areas, particularly in the dry season, judicious management strategies have been suggested in the literature and are reviewed here.

Based on modeling results, Vertessy et al. (2003) suggest that planting trees away from streams, i.e., in areas with a deeper water table, considerably helps protect ground water storage and baseflow. Bayer (2014, p. 21-22) provides a brief literature review on the topic of impacts of changes in riparian vegetation, concluding that they bring the largest changes in streamflow (Figure 28). Although beyond the scope of this literature review, there may however be considerable ecological and water quality benefits of riparian forests.

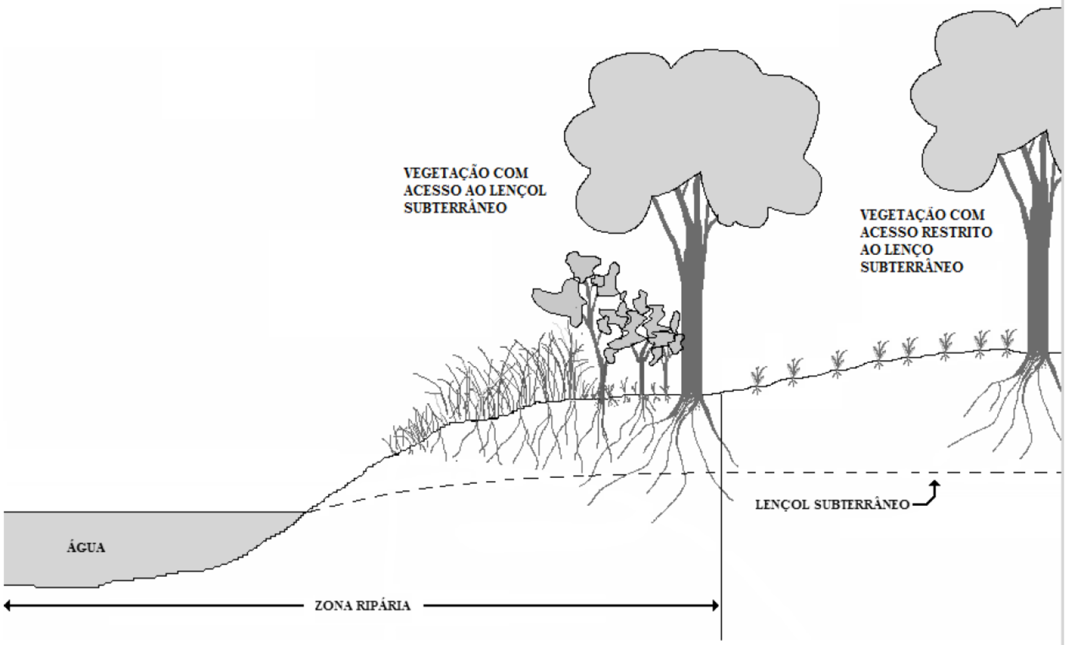


Figure 28. Changes in riparian land cover have the largest consequences to streamflows, particularly in the dry season. The figure labels read "Vegetation with access to the ground water table", and "Vegetation with restricted access to the ground water table". This figure is reproduced from Bayer (2014).

The importance of soil conservation in groundwater recharge areas was emphasized in the study of soil core samples conducted by Resck (2005) in the Taquara watershed, a tributary of the São Bartolomeu River in the Cerrado biome region. Also, in many areas, trees planting on the downslope edge of cropland are least likely to compete for water resources, instead consuming excess water from upslope. Therefore, the perimeter-to-area ratio and the alignment along contours may influence water use (e.g., Silberstein et al., 2002). Forest edges may also capture wind-driven rain and fog (Weathers et al., 2005) enhancing local precipitation.

Conversion of agricultural land to plantation forestry is often associated with an extension of access infrastructure, including roads, tracks and firebreaks, whose design and maintenance carries important consequences to hydrology and soil erosion (van Dijk and Keenan, 2007).

Citing evidence that evapotranspiration is higher along the edges of afforested areas (Taylor et al., 2001), due to higher wind speeds and air turbulence, Vanclay (2009) suggests incorporating windbreaks into plantation design (to lower wind speed) and surrounding the tree stands with hedges (to reduce air turbulence). Windbreaks would consist of a "carefully chosen species" with favorable canopy characteristics and a strong capability using stomatal control to regulate its water loss. While Vanclay (2009) is not able to identify specific favorable species, he recommends the development of future research using field studies of sap flux density in existing plantations, in the manner of Herbst et al. (2007) and Schiller et al. (2007). Vanclay (2009) cites Morse et al. (2002) on the value of surrounding the afforested area with hedges to reduce air turbulence, and recommends further research through a) experimental modification of existing plantation edges, and b) simulation modeling (Krizkalla, 2005).

Citing evidence that mixed species plantings may have a canopy structure that is less coupled to the atmosphere than single-species plantings (Forrester, 2007), Vanclay (2009) suggests using heterogenous tree species to reduce evapotranspiration. Vanclay (2009) recommends the development of future research in existing mixed-species stands, using sap flow measurements (Oltchev et al., 2002) and eddy-covariance flux measurements (Kurpius et al., 2003; Blanken and Black, 2004; Zhang et al., 2006).

4 CONCLUSIONS

Forests exhibit higher evapotranspiration rates compared to shorter vegetation, a difference that is largest in the dry season when the trees' deep roots can access ground water reserves not available to the shallower roots of other vegetation. The higher evapotranspiration from forests carries different implications, which in this document were presented in conceptualized form as five mechanisms (Table 4, which was also presented, as Table 1, in the executive summary section).

Table 4. Five major physical mechanisms by which forests' high evapotranspiration rates influence precipitation and hydrology. The direction of the effect, positive of negative, is indicated for each variable.

Mechanism:		*Effect on:*		
		Precipitation	**Streamflow**	**Groundwater Storage and Baseflow**
Influence on the atmosphere:				
I.	*Atmospheric moisture recycling*	+	+	+
II.	*Local land-atmosphere interactions*	+	+	+
III.	*Influence on large-scale atmospheric circulation*	+	+	+
Influence on hydrologic pathways:				
IV.	*Reduced water yield*		–	–
V.	*Increased soil permeability*		–	+

The first three mechanisms in Table 1 pertain to the influence of high evapotranspiration rates on precipitation. Each of the three mechanisms has ample theoretical and observational support in the scientific literature, some of which we reviewed in this document. These mechanisms act at different spatial scales.

The overwhelming majority of the scientific literature restricts itself to one or another of these mechanisms in isolation, usually without mentioning the others. This is a significant point because, in our assessment, this results in partial and incomplete frameworks of analysis that are mutually disconnected and can lead to conflicting or paradoxical conclusions. Consideration of mechanisms I, II, and III, together is essential for correct interpretation of observations and modeled results alike.

That changes in evapotranspiration in tropical forested regions are capable of altering large-scale atmospheric circulation patterns and intensity (mechanism III), thereby causing changes in precipitation, has been recognized for several decades. The influence of the high evapotranspiration from the tropical South American forests on the Hadley-Walker circulation has long been understood on theoretical and modeling grounds. The Hadley-Walker circulation represents the global conveyor belt that redistributes water and energy from the tropics to the subtropics.

The depth of tree roots, which allows forests to maintain high evapotranspiration rates throughout the dry season, was shown to be a key factor in mechanism III. Indeed, LBA flux tower measurements documented the occurrence of annual maximum evapotranspiration rates in the dry season for several forested areas. Mechanism III is embedded in climate simulations and future climate projections (as a result of thermal effects associated with the large amounts of heat released to the atmosphere by evapotranspiration), and it wouldn’t be possible to achieve any modeling realism without it.

Recently, it was proposed that in addition to the classical thermal phenomena, there is an additional phenomenon that has so far been neglected and, when included, further strengthens mechanism III considerably. The proposition is that the loss of mass from the atmosphere during the process of condensation results in a significant drop in air pressure which, if explicitly incorporated in climate models, has important effects. The general physical phenomenon that is being referred to has long been recognized, however, the mathematical formulation of its strength is surprisingly difficult and contentious. The proponents of the far-reaching formulation, known as the “biotic pump” theory, are Anastassia Makarieva and Victor Gorshkov, researchers of the Theoretical Physics division of Russia’s Petersburg Nuclear Physics Institute, who frequently collaborate with Brazilian researchers and have led a series of intriguing manuscripts published in the last decade.

In our review of the scientific literature, we found numerous instances of misunderstanding, where the manuscripts appear to equate mechanism III with the biotic pump theory only, not realizing that the biotic pump theory is only one of the possible contributing explanations for mechanism III, which predates this particular theory by several decades. This confusion is significant because the biotic pump theory remains contentious, with important aspects of its mathematical formulation having been challenged by Meesters et al. (2009), receiving a response in Makarieva and Gorshkov (2009b), and there not appearing to be a widespread agreement about it in the scientific community. Theoretical scrutiny of the theory is made difficulty in part because the highly advanced formulation makes it difficult to follow for many researchers.

The confusion is also significant because, when it is (wrongly) believed that the biotic pump theory being the only explanation for mechanism III, there is a risk that any evidence supporting mechanism III will be interpreted as confirmation for the biotic pump theory. The biotic pump theory has compared favorably to observations, but in our view it has not been shown in the scientific literature reviewed that previous physical-mathematical formulations of mechanism III are not also in agreement to observations. For example, Poveda et al. (2014) state they are performing testing the biotic pump theory, and Nobre (2014) states that Poveda et al. (2014) has provided observational confirmation of the biotic pump theory. However, in a more detailed reading of Poveda et al. (2014) we find the possibility is left open that the more traditional physical basis for mechanism III may suffice to explain the results. They write (p. 99): *"It could be explained by (1) surface convergence favored by the release of latent heat in the region's extraordinarily intense storms and mesoscale convective systems and (2) atmospheric pressure gradients created by the condensation of water vapor evapotranspired by the tropical rainforest (…)"* Explanation (1) refers to the traditional physical basis for mechanism III, while explanation (2) is the biotic pump theory.

All formulations of the forces driving mechanism III – either the more traditional formulations based on the atmosphere's thermal gradients, or those unrelated to the biotic pump theory as formulated by Makarieva and Gorshkov – have very great consequences for science and policy at a global scale. Because of this mechanism's importance, it is deserving of intense further research leading to the scrutiny of its theoretical components, and rigorous testing using observational evidence, with the goal of establishing a resilient theory. One of the consequences of mechanism III, with particularly major consequences to forest policy worldwide, is that the high evapotranspiration rates associated with a densely forested region bring in humid air masses and, therefore, the elimination of these forests would lead to much drier conditions – which, eventually, would preclude future forest regrowth, originating a stable new dry climate.

Some researchers have suggested that the topical forests' high evapotranspiration throughout the dry season is an indication that it is resilient to droughts. In this literature review, we found such evidence to be lacking. To the contrary, the Amazon's forests suffered considerable losses during the severe droughts of 2005 and 2010. In 2005, researchers reported large losses in biomass in the areas affected (due only in part to thunderstorms and wild fires). Such losses were consistent with the results from the deliberate drought experiments where rainfall was consistently siphoned off from test plots of forest (e.g., Costa et al., 2010). The 2010 drought was spatially more widespread, affecting over half of the Amazon's area, and resulting in the lowest streamflow ever recorded at Manaus.

It is hypothesized by many researchers that the 2005 and 2010 droughts were not isolated incidents, but the culmination of generally drier conditions observed from about 1970 to present. Wang et al. (2011) suggested that vegetation dynamics gives rise to persistence of precipitation anomalies across multi-year periods. This is possible due to the strong coupling between soil moisture and precipitation, mediated by the forests – as demonstrated in Wang et al.'s (2011) modeling experiments, reviewed in section 2.6. Saatchi et al. (2013) documented the persistence of canopy damage after the 2005 drought.

Wang et al. (2011) conclude as follows, ending in an important admonition: *"Due to the damping effects of vegetation, the several years following a severe drought in a region may be more prone to recurrent droughts, making it more likely for drought years to occur as a cluster. A similar statement holds for flood years. In the Amazon region, the past decade witnessed two extreme droughts, one in 2005 and a much more severe one in 2010 that coincided with the local dry season [e.g., Marengo et al., 2008, 2011; Lewis et al., 2011; Xu et al., 2011]. The drought in 2010, a "once-in-a-century" event, caused substantial reduction of vegetation greenness across the Amazon basin south of the equator that did not recover when the rainy season precipitation returned to normal [Xu et al., 2011]. Results from our study suggests that, in absence of extremely strong oceanic forcing favoring precipitation in this region, many areas of Amazon will be prone to recurrent droughts in the several years following the 2010 drought."*

Having shown us how major canopy damage (caused by the 2005 drought) can lead to increased likelihood of future droughts, the years 2005 and 2010 brought home the message of just how important the forests are maintaining dry season precipitation rates throughout northern and central South America.

Given the multiple benefits of forests, including in maintaining precipitation through vast regions of South America, there are good reasons to take advantage of degraded areas to promote afforestation (or reforestation). What localized effects might we expect following the afforestation of a degraded are? The structure and permeability of the soil will recover gradually due to the beneficial effect of root development, as well as gradual increase in the thickness and quality of the soil, particularly humic complexes which are formed in the layer of fallen leaves in soil. The increased permeability contributes to decrease runoff and increase soil moisture and groundwater recharge. Humic complex also contribute to the retention of soil moisture.

The reforestation of degraded areas will introduce a tendency to greater water loss through evapotranspiration (mechanism IV), but on the other, a tendency to lower losses by lateral flow quickly to the surface or shallow (mechanism V). The effect on the availability of local water will depend on the balance these two opposing tendencies. And this balance depends on the specific local factors of climate, soil, topography and specific location of the reforested area.

Through mechanisms I, II, and III, the forests bring and maintain moisture over vast regions of South America (section 2), and their dominant effects on surface and subsurface runoff are overwhelmingly positive. This is a principal finding of our literature research. Through mechanism IV, localized effects of afforestation will in most cases lower surface and subsurface runoff (section 3), although management strategies are available to minimize local effects (section 3.2). Through mechanism V, localized effects of afforestation may enhance sub-surface flow through the improvement of soil infiltration capacity and drainage, although many years, up to a few decades, may be required to achieve significant soil changes. This is especially likely to occur in previously degraded areas.

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