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Preface

Hydrological and biogeochemical processes in a changing Amazon: results from small watershed studies and the large-scale biosphere-atmosphere experiment

Christopher Neill,[1]* Helmut Elsenbeer,[2] Alex V. Krusche,[3] Johannes Lehmann,[4] Daniel Markewitz[5] and Ricardo de O. Figueiredo[6]

[1] *The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, USA*
[2] *Institute of Geoecology, University of Potsdam, Potsdam, Germany*
[3] *Centro de Energia Nuclear na Agricultura, University of São Paulo, Piracicaba, SP, Brazil*
[4] *Department of Crop and Soil Sciences, Cornell University, Ithaca, NY, USA*
[5] *Daniel B. Warnell School of Forest Resources, University of Georgia, Athens, GA, USA*
[6] *Embrapa Amazonia Oriental, Avenida Enéas Pinheiro, Belém, PA, Brazil*

Abstract:

The Amazon Basin is the world's largest tropical forest region and one where rapid human changes to land cover have the potential to cause significant changes to hydrological and biogeochemical processes. The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is a multidisciplinary, multinational research program led by Brazil. The goal of LBA is to understand how the Amazon Basin functions as a regional entity in the earth system and how these functions are changing as a result of ongoing human activity. This compilation of nine papers focuses on a central LBA question in the area of nutrient dynamics and surface water chemistry—how do changes in land use alter fluxes of dissolved and particulate materials from uplands across riparian zones and down the channels of river corridors? These papers cover work conducted in small watersheds on a wide range of topics within the spirit and geographical focus area of LBA: water balance and runoff generation, nutrient transformations in riparian zones and stream channels, carbon fluxes in water moving from land to water and the influence of soils on flowpath structure and stream chemistry. Important new insights can be gained from these and other studies. Forest clearing for pastures results in a decrease in soil hydraulic conductivity that forces water into surficial flowpaths throughout most of the rainy season across wide regions of the Amazon. Riparian zones along small forest streams appear to be very effective in removing nitrate arriving from the uplands, while forest streams take up nitrate at very low rates, allowing them to travel downstream for long distances. Although substantial, the contribution of dissolved organic C (DOC) to the carbon flux from forests to streams appears to be lower than the flux of dissolved inorganic C that is subsequently outgassed as CO_2. Remaining key challenges within LBA will be to synthesize existing data sets on river networks, soils, climate, land use and planned infrastructure for the Amazon to develop models capable of predicting hydrologic and biogeochemical fluxes at a variety of scales relevant to the development of strategies for sustainable management of the Amazon's remarkable forest, soil and freshwater resources.

KEY WORDS water balance; runoff; riparian zone; stream chemistry

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* Correspondence to: Christopher Neill, The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, USA.
E-mail: cneill@mbl.edu

INTRODUCTION

Small watershed studies have provided some of our most important insights into hydrological and biogeochemical functions in forest ecosystems. They have contributed enormously to understanding how rainwater becomes runoff (Dunne and Black, 1970), how dynamic hydrological flowpaths contribute to the generation of stream flows (Hooper *et al*., 1990; Kendall and McDonnell, 1998) and how these processes can be captured in models of stream flow and storm flow generation (Beven and Kirkby, 1979). Studies of small watersheds also have provided some of the first and best information on biogeochemical budgets at the scale of entire ecosystems (Likens *et al*., 1967; Johnson and Swank, 1973). Comparisons and experimental manipulations conducted in small watersheds have been invaluable for answering important questions about how human-induced changes—such as clearing, silvacultural practices, atmospheric deposition or climate change—influence hydrological and biogeochemical processes in forest ecosystems (Swank and Crossley, 1988; Bormann and Likens, 1994; Lovett *et al*., 2000; Palmer *et al*., 2004). Gains in the understanding of hydrological and biogeochemical processes made possible by the advantages of working at the small whole-watershed scale are increasingly relied on to make predictions about responses to human activities at larger scales.

It is no surprise then that there is an important role for studies in small experimental watersheds within the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). LBA is an interdisciplinary, multinational research program led by Brazil that attempts to understand the ecological and biogeochemical functioning of the natural ecosystems of the Amazon Basin and how this functioning is changing given the rapid alterations to the cover and use of land that are now occurring (Richey *et al*., 1997). The overall question guiding research in LBA is: 'How do tropical forest conversion, regrowth and selective logging influence carbon storage, nutrient dynamics and trace gas fluxes and the prospect for sustainable land use in the Amazon region?' (Keller *et al*., 2004). *Nutrient dynamics and surface water chemistry* is one of the four major subject areas for ecological research within LBA (*land use and land-cover change, carbon dynamics*, and *trace gas and aerosol fluxes* are the others). The key question for surface water chemistry in LBA is: 'How do changes in land use and climate alter the stocks, processes and fluxes of dissolved and particulate organic matter, nutrients and trace gases from the uplands across riparian zones and floodplains and down the channels of river corridors?'

A number of perspectives are implicit in the overall design of LBA research focused on this question. First, there is a need to understand how water and dissolved and particulate material move from land into streams and downstream in stream networks within 'primary' or predisturbance Amazon ecosystems. This basic understanding of natural ecosystem function provides an essential baseline from which to evaluate any human-caused changes. Second, it is neither desirable nor possible to separate the investigation of water movement from investigation of solute and particulate transformations and fluxes. The two have proceeded in an integrated fashion inside LBA. Third, the Amazon is a large and diverse region that incorporates substantial variability in topography, soils, vegetation and climate. How these factors influence movement of water and dissolved and particulate material is a key to development of understanding at larger scales. Topography, soils, vegetation and climate will interact with human-caused changes to land cover in important ways. Only through understanding of these interactions will it ultimately be possible to predict how Amazon ecosystems are likely to respond to increased human presence and activity. It is this integrated understanding, achieved by interaction and collaboration across nations and among scientific teams, that LBA has sought to foster. The results of these studies will be of enormous value in shaping policies that control the location, extent and character of the human-dominated systems that are likely to replace many natural ecosystems of the Amazon in the future. Within this context, small watershed studies in the Amazon have much to contribute.

In this paper, we briefly review key issues and challenges for research linking hydrology and biogeochemistry in small watersheds of the Amazon Basin (Figure 1). Then, we review the results and contributions from nine studies in this issue that demonstrate how work in small Amazon watersheds is addressing the main science questions posed by LBA. These studies were conducted at sites ranging from montane forests

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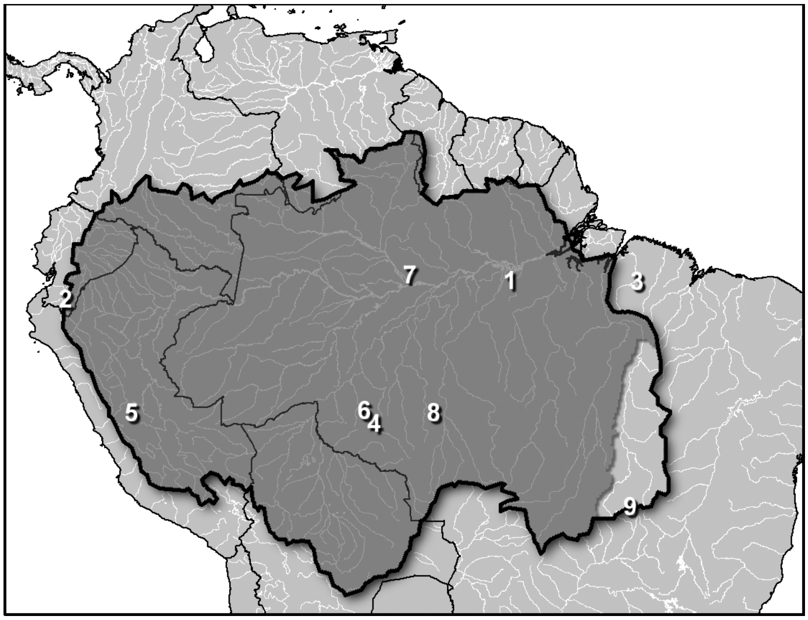

Figure 1. Location of studies covered in this issue. The dark line delineates the Amazon Drainage Basin. The lighter area east of the Amazon is the Tocantins River Basin. Numbers are: 1, Bruno, *et al.*; 2, Fleischbein, *et al.*; 3, Moraes, *et al.*; 4, Biggs, *et al.*; 5, Saunders, *et al.*; 6, Neill, *et al.*, 7, Waterloo, *et al.*; 8, Johnson, *et al.*; 9, Markewitz, *et al.*

of Ecuador and the Andean region of Peru, to the Amazon lowlands of the Brazilian states of Rondônia, Amazonas and Pará, and the savanna biome that technically lies mostly outside the Amazon hydrographic basin but inside the scope of LBA. We conclude by identifying emerging patterns and challenges that will guide work in the future.

AMAZON WATERSHEDS

The Amazon is the largest and arguably the most important tropical river basin on earth. The Amazon drainage spans seven countries, covers 6 869 000 km^2 of land area and contains more than twice as much tropical forest as tropical Asia and Africa combined (Achard *et al.*, 2002; Goulding *et al.*, 2003). The Amazon River itself has three major tributaries more than 3000 km long and discharges more than 15% of the world's annual fresh water into the ocean, a flow roughly equal to that of the earth's next six largest rivers combined (Pekárova *et al.*, 2003).

Despite the enormity of the mainstem Amazon River and its tributaries, most of the water still enters these great rivers in small watersheds. First- and second-order streams account for 84% of total stream length in the 3300 km^2 Cueiras Basin of the lowland central Amazon (McClain and Elsenbeer, 2001) and 74% of total stream length in the 75 000 km^2 Ji-Paraná Basin of the lowland western Amazon (Ballester *et al.*, 2003). Adjacent terrestrial ecosystems play a dominant role in shaping the hydrology and biogeochemistry of these small streams and their watersheds. Small stream channels are linked to the land by groundwater flows, surface and subsurface runoff, seepage from riparian zones and direct inputs of throughfall and terrestrial detritus. It is in understanding these connections—and how flows of water are linked to biogeochemical transformations and movements of dissolved and particulate materials—where small watershed studies are yielding their most important insights. And only studies of small watersheds allow the quantification of all flowpaths that enable us to draw mechanistic conclusions about processes at the terrestrial-aquatic interface.

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It is also in small watersheds where the consequences of changes to Amazon land use are most acute. The Amazon is changing rapidly because forests are being cleared by logging and for expanding agriculture and urban areas. Deforestation in the Brazilian portion of the Amazon has ranged from 11 000 to 29 000 km^2 y^{-1} from 1988 to 2004 (INPE, 2004). Approximately 15% (or 630 000 km^2) of the formerly forested area of the Brazilian Amazon has been cleared. Most of the cleared area is used for cattle pasture, but use of cleared forest for large-scale crop production, particularly soybeans, is also increasing rapidly (Fearnside, 2001). In addition, logging now alters an area nearly as large as direct clearing (Asner *et al*., 2005) and fragmentation of the remaining forest coupled with fire threaten to alter still larger areas (Nepstad *et al*., 2001).

While the continuous canopy of remaining Amazon forest may appear uniform when viewed from the air, this belies the complexity and potential importance of the underlying soils. The diversity of Amazon soils rivals that in temperate regions (Richter and Babbar, 1991). Soils range from nearly 100% sand to more than 80% clay and vary widely in their hydraulic characteristics (Elsenbeer and Lack, 1996), mineralogy and weatherable minerals (Sombroek, 2000). Physical and chemical characteristics of soil play a large role in determining the productivity and sustainability of agriculture on cleared land (Davidson *et al*., 2004), the mechanisms by which runoff is generated (Elsenbeer, 2001) and the composition of dissolved solutes in stream waters (Biggs *et al*., 2002). Understanding how the nature and properties of soils interact with land cover change to control hydrological and biogeochemical processes is central to the core mission of LBA.

WATER BALANCE AND RUNOFF GENERATION

How and when does water move from watersheds into stream channels? What does that water carry with it? How will the mechanisms by which water and materials move be altered by replacement of native Amazon forest with agricultural land covers? These are seemingly simple but critical questions for understanding hydrological and biogeochemical responses in a changing Amazon. Replacement of forest with pasture or other agricultural land covers influences hydrological properties of soils, the balance between rainfall and evapotranspiration, and consequently runoff responses in watersheds. High surface albedo, lower leaf area and shallower rooting depths of pastures compared with forest contribute to reduced evapotranspiration (Costa and Foley, 1997; Bruijnzeel, 2004). Reviews of small catchment studies throughout the world almost invariably demonstrate that deforestation leads to higher stream flow (Bosch and Hewlett, 1982). Although less numerous, a growing number of studies from tropical regions suggest that complete removal of natural forest cover increases water yields by 200–800 mm y^{-1}, depending on rainfall and the degree of surface disturbance (Malmer, 1992; Bruijnzeel, 1996; Sahin and Hall, 1996; Bruijnzeel, 2004). Similar increases in discharge have now been detected at a larger scale in the 175 360 km^2 Tocantins River Basin in the southeastern Amazon (Costa *et al*., 2003).

Two papers in this issue provide new information on water balance in natural Amazon forests. Bruno *et al*. (2006) used time-domain reflectometry to make continuous measurements of soil moisture in a lowland forest near Santarém in Pará state. They provide new details on the spatial dynamics of water withdrawal from deep soils and show that the active depth of soil water withdrawal varies during the annual wet-dry precipitation cycle, with surface (0–2 m) soils providing the majority of water for transpiration during the wet season, but deeper soils (2–20 m) supplying nearly three-fourths of the water needed to sustain transpiration in the dry season. This reliance on deep rooting sustains forest evergreenness through dry seasons that can last up to 6 months over large areas of lowland Amazonia (Nepstad *et al*., 1994). Bruno *et al*. validate their estimates of evapotranspiration by comparison with estimates of canopy water vapour flux estimated by eddy covariance at the same site.

From the central lowlands to the Andes, the Amazon encompasses great variation in the amounts and dynamics of precipitation (Sombroek, 2001). This pattern interacts with the biomass and structure of forests (Malhi *et al*., 2004) to shape components of water balance. Fleischbein *et al*. (2006) used a combination of hydrological measurements and modelled surface flows to show that interception losses account for

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40% of precipitation in three catchments in Ecuadorian montane forest at 1900–2200 m elevation. This interception, plus the steep topography and frequency of landslides in these Andean Amazon forests, suggest that deforestation would have disproportionately large consequences for runoff generation and erosion at the landscape scale.

The forest clearing and installation of the permanent agriculture that now dominate deforested areas in the Amazon result in a number of important changes to the physical and chemical properties of soils that influence runoff generation and the material carried by water moving from land to water. Soil compaction reduces soil hydraulic conductivity in cattle pastures created from cleared Amazon forests and hence can greatly increase the amount of water that leaves small watersheds as near-surface or overland flow. Moraes *et al*. (2006) and Biggs *et al*. (2006) provide important new details about how runoff is generated from Amazon pastures. In the eastern Amazon state of Pará, Moraes *et al*. found that strong vertical gradients of soil saturated hydraulic conductivity limited vertical drainage and kept soil water contents close to saturation during the wet season in both forest and pasture. Decreased soil hydraulic conductivity in pastures led to a fivefold increase in water exported as quickflow from first-order streams in pasture compared with forest. They found that both saturation overland flow and infiltration-excess overland flow contributed to streamflow in the pasture watershed and that overland flows amounted to 17% of rainfall. In the forest watershed, all overland flow originated from saturated areas and it amounted to less than 3% of rainfall. At larger scales, this shunting of water into overland flowpaths during the wet season in deforested portions of watersheds may become more important than weathering in the delivery of materials such as Ca or other cations from land into streams (Markewitz *et al*., 2001).

In the western Amazon state of Rondônia, Biggs *et al*. (2006) used field measurements, an annual water balance and a Soil Conservation Service curve number model to estimate runoff from different contributing areas in a watershed of established cattle pasture. They estimated that infiltration-excess overland flow and saturation overland flow originating in the near-stream zone contributed in roughly equal proportions to stream runoff and that these flows also amounted to 17% of rainfall, nearly identical to the Pará watersheds. By differentiating the origin of flowpaths derived form upslope saturation-excess, near-stream saturation flow and water exported in groundwater from upslope in the catchment, and by measuring concentrations of solutes in the flowpaths, Biggs *et al*. estimated the importance of each flowpath to total solute export. While groundwater export and not stream flows dominated the small catchment water budget, saturation-excess flow from upslope supplied more than half of phosphorus export, and near-stream zones were responsible for nearly 75% of inorganic and total nitrogen (N) export. There are two important take-home messages from these reports. First, they provide strong evidence of how changes in soil conductivity following deforestation clearly route an increasing amount of water into overland flowpaths and first-order stream channels. Second, the approach of combining estimates of flowpath contributions to stream flow with measurements of solute concentrations is clearly an important step towards determining the mechanisms by which deforestation and other land-use changes now alter the chemical composition of water entering Amazonian steams from land.

RIPARIAN ZONES AND SMALL STREAM CHANNELS

How much stream water going into streams in small watersheds actually moves through riparian zones? How are solutes and suspended materials transformed by contact with soils and oxidation-reduction conditions in riparian zones? These are important questions for understanding controls on stream water chemistry and for potentially mitigating and managing land-use changes over large areas in watersheds. Riparian areas have long been thought to be important sites for processing water that arrives from the upland portions of watersheds. Riparian zones in tropical streams may be particularly important for controlling the amount of N that enters stream waters. This is because N in primary tropical forests behaves largely as if vegetation and soils are N saturated. Rates of N mineralization and nitrification in soils are typically high (Neill *et al*., 1997; Davidson *et al*., 2000), leading to concentrations of NO_3^- in the soil solution of tropical forests that exceed those

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typically found in temperate forests (Neill *et al.*, 2001; Davidson *et al.*, 2004; Markewitz *et al.*, 2004). At the same time, concentrations and fluxes of NO_3^- and total dissolved inorganic N in small streams draining lowland Amazon forest are low and typically two orders of magnitude less than concentrations in soil solution (Lesack, 1993; Neill *et al.*, 2001; Markewitz *et al.*, 2004). This, coupled with sharp decreases in soil solution NO_3^- in gradients from upland to streams at least in several forest locations (McDowell *et al.*, 1992; McClain *et al.*, 1994; Williams *et al.*, 1997) supports arguments for high N removal as water passes through riparian zones.

Saunders *et al.* (2006) provide additional evidence that nitrate concentrations decrease sharply along flowpaths from upland forest and through riparian areas to streams in Peruvian headwater streams. In contrast to most lowland locations where concentrations of soluble reactive phosphate (SRP) are extremely low in both soil solution and streamwater, Saunders *et al.* found the opposite trend, with higher SRP concentrations in streamwater. They also found dissolved organic N and P dominated dissolved N and P fluxes in stream water. This was similar to the patterns observed in streams draining South American old-growth temperate forests in a region of equivalent low N deposition (Perakis and Hedin, 2002), but differs from patterns in a number of lowland forests in the Amazon and elsewhere where nitrate is a much more important component of soil solution and streamwater (Neill *et al.*, 2001; Markewitz *et al.*, 2004; Schwendenmann and Veldkamp, 2005). While the findings of Saunders *et al.* suggest that patterns of N removal in riparian zones solution and streams may be qualitatively similar in different Amazon forests, understanding exactly how water moves through and is processed in riparian zones in a range of Amazon locations will depend on the application of emerging techniques that delineate hydrological flowpaths in small catchments across a range of soils and geology (McGlynn and McDonnell, 2003).

Recent work that shows small headwater streams play large roles in transforming N and regulating its movement downstream (Mulholland *et al.*, 2000; Peterson *et al.*, 2001) make it clear that hydrological and biogeochemical processes within streams themselves can be as important as those in riparian zones and soils of watersheds in regulating water and solute movement from land to larger streams. Changes in land use alter hydrological and biogeochemical processes within stream channels, but these changes have received relatively little attention. Neill *et al.* (2006) used solute injection experiments to characterize water and solute movement through forest and pasture stream channels draining watersheds of 1–17 km^2 in Rondônia. They found that changes in physical and biogeochemical conditions in pasture streams caused by infilling by pasture grasses led to longer water residence times, greater transient water storage and declines in dissolved oxygen compared with forest streams. In turn, these conditions were associated with increases in SRP and ferrous iron concentrations. Neill *et al.* found that uptake rates for inorganic N in both forest and pasture streams were low compared with the temperate streams where these processes have been studied. Forest streams also exhibited no uptake of nitrate, suggesting that once nitrate reaches streams in hydrological flowpaths through or around riparian zones it has the potential to travel long distances into larger streams and rivers.

CARBON FLUXES

How much carbon (C) that is fixed by forest plants 'leaks' into ground water and exits watersheds either in the form of dissolved organic C (DOC) or by degassing as CO_2 along stream margins? Is this a significant portion of the C measured by canopy exchange techniques to be stored annually by old-growth forests? Recent measurements of net ecosystem exchange (NEE) of C between lowland Amazon forests and the atmosphere made from eddy covariance measurements of CO_2 exchange across forest canopies and from inventories of forest biomass indicate that NEE and C accumulation or loss is low and on the order of 0 ± 2 Mg C ha^{-1} y^{-1} (Arújo *et al.*, 2002; Miller *et al.*, 2004; Rice *et al.*, 2004; Vourlitis *et al.*, 2004). Because river and floodplain waters of the Amazon have partial pressures of CO_2 that are supersaturated with respect to the atmosphere, water that reaches streams and rivers or exchanges with floodplains has the potential to be a conduit for transporting dissolved C from terrestrial ecosystems to surface waters where it is subsequently released to

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the atmosphere. Richey *et al.* (2002) recently estimated that outgassing of CO_2 from rivers could account for $1{\cdot}2 \pm 0{\cdot}3$ Mg C ha^{-1} y^{-1} released to the atmosphere over a 1·77 million km^2 area of the central Amazon, a flux that is similar to NEE for terrestrial forests and is more than ten times the C exported to the ocean by the Amazon River.

Richey *et al.* (2002) hypothesized that the evasion is driven by respiration of organic C fixed on land or along river margins and transported to surface waters. Transport of particulate C, DOC and the CO_2 resulting from respiration of organic matter in flowpaths during transit to streams all potentially contribute to the total flux. This raises another important question, what are the sources of the potentially large amount of C moving from land to surface waters? Papers by Waterloo *et al.* (2006) and Johnson *et al.* (2006) examine the transport of organic C in small forest watersheds in Amazonas and Mato Grosso states. Waterloo *et al.* tracked exports of C as particulates and as DOC for 2 years in the 6·8 km^2 blackwater Igarapé Açu catchment in the Rio Negro Basin near Manaus. Fluxes as DOC comprised more than 98% of total DOC plus particulate organic C export of 19 g m^{-2} y^{-1}. The form and magnitude of DOC export per unit land area of watershed from the Açu catchment were very similar to the fluxes previously estimated for the entire Rio Negro Basin (Richey *et al.*, 1990), but they averaged only 5–6% of net ecosystem C accumulation measured by eddy covariance at nearby towers and were lower than the 15% of evasion attributed to DOC export on sandy spodosols by Richey *et al.* (2002).

Johnson *et al.* (2006) quantified DOC and particulate organic C fluxes from four 1–2 ha watersheds drained by first-order clearwater streams on a combination of clayey Oxisols and Ultisols near Juruena, Mato Grosso, and found much lower annual fluxes of DOC (3·2 g m^{-2} y^{-1}) but higher export of particulate C (1·8 g m^{-2} y^{-1}) compared with the Açu catchment. The sum of DOC and particulate C fluxes from these watersheds were insufficient to account for the bulk of the measured C sink in Amazon forests, but they still leave open the possibility that ground water or other land-to-water flowpaths are delivering waters supersaturated in CO_2 that outgas near soil-stream interfaces. There is growing evidence that local sources of C rather than long-distance transport of refractory DOC drive outgassing in larger Amazon rivers (Mayorga *et al.*, 2005), but there is still much to be learned about the sources and magnitudes of land-water C transfers of dissolved inorganic C in small watersheds where streams are most intimately connected with terrestrial ecosystems. Fluxes of CO_2 to the atmosphere in these headwater streams occur far from the larger rivers where most measurements of CO_2 supersaturation in Amazon surface waters have been made.

SOIL AND VEGETATION CONTROL OF STREAM CHEMISTRY

How does the diversity of soils in the Amazon influence the chemistry of streams and rivers? How will soil physical properties and chemistry influence hydrological and biogeochemical responses to deforestation? Soil fertility in the Amazon, particularly base cation status, is linked to ecosystem properties that range from biological diversity (Sombroek, 2000) and above-ground tree productivity (Malhi *et al.*, 2004) to stream water fluxes of major ions (Biggs *et al.*, 2002; Ballester *et al.*, 2003). Ion concentrations are typically lower in streams draining more highly weathered soils, but characterizations of most ions and forms of dissolved N and P have still been conducted in few locations across the diversity of Amazon soils and vegetation. Markewitz *et al.* (2006) demonstrate one end of the range of that variability. While technically outside the Amazon Basin, they measured both soil and stream water base cation and N and P chemistry in a 1200 ha watershed of the Roncador stream draining cerrado (savanna) vegetation on oxisols of the Brazilian Shield near Brasilia. This lies on soils that are extremely depauperate of cations that are representative of soils that underlie the cerrado vegetation along the eastern boundary of the Amazon drainage area (Haridasan, 2001). Markewitz *et al.* found that the proportional abundance of dissolved ions was broadly similar to other Amazon rivers but that stream water cation concentrations were at the very low end of the range observed in Amazon and other South American lowland tropical rivers, far below those reported for the Andes and the western Amazon but close to those in the Rio Negro (Stallard, 1985; Edmonds *et al.*, 1995; Ballester *et al.*, 2003; Mortatti and Probst, 2003). Relationships of discharge and cation concentrations in the Roncador stream

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indicated that groundwater still supplied cations from weathered parent material and that riparian zones may play an important role in controlling stream cation concentrations.

FUTURE CHALLENGES

The next challenges in LBA will be to use site-specific information gathered in studies of small watersheds and measurements in dozens of forests, pastures, regrowing forests and cropping systems to build the capacity to predict hydrological and biogeochemical responses in a future Amazon that will likely be substantially different from the past or current Amazon. LBA has generated important new data sets on river networks, soils, climate, land use and planned infrastructure for the Amazon region. Key experiments and measurements coupled with ecosystem biogeochemical models now allow extrapolation of trace gas fluxes and C balance over large regions (Keller *et al*., 2004). Models of water routing are still improving but now allow simulation of discharge at very large scales (Coe *et al*., 2002). But there are major challenges ahead. What is absent is the ability to confidently model land-water transfers and fluxes of water and materials from small- and medium-sized Amazon watersheds. These are the scales at which (i) ranchers want to know if streams will flow in the dry season as more land is deforested, (ii) resource managers want to know if increased sediment or nutrients downstream caused by deforestation will affect water quality and fish production in larger rivers, and (iii) legislators and government agencies want to know if leaving more forest in riparian buffers will improve water quality and buffer storm flows. LBA science has provided much valuable information on which to base decisions about sustainable management of the Amazon's remarkable forest, soil and freshwater resources. In many ways, the remaining challenges within LBA do not stand apart from the challenges of modelling complex and linked hydrological and biogeochemical processes at the landscape level in other important and rapidly changing locations on earth.

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