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Land–Water interactions in the amazon

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Abstract Biogeochemistry is hosting this special thematic issue devoted to studies of land–water interactions, as part of the Large-scale Biosphere–Atmosphere Experiment in Amazônia (LBA). This compilation of papers covers a broad range of topics with a common theme of coupling land and water processes, across pristine and impacted systems. Findings highlighted that hydrologic flowpaths are clearly important across basin size and structure in determining how water and solutes reach streams. Land-use changes have pronounced impacts on flowpaths, and subsequently, on stream chemistry, from small streams to large rivers. Carbon is produced and transformed across a broad array of fluvial environments and wetlands. Surface waters are not only driven by, but provide feedback to, the atmosphere.

Keywords Land-use change · Flowpaths · Stream chemistry · Scaling · Cloud streets · Carbon cycling

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Overview

The Amazon is both a river and a forest, but the scientific communities that study aquatic and terrestrial processes in this huge biome often do so in isolation of each other. Hence, Biogeochemistry is delighted to host a special thematic issue devoted to land–water interactions that were studied as part of the Large-scale Biosphere–Atmosphere Experiment in Amazônia (LBA), a multinational, interdisciplinary research program led by Brazil. The goal of LBA is to understand how Amazônia functions as a regional entity in the Earth system and how those functions are changing as the result of ongoing changes in land use. In addition to the approximately 7 million km^2 Amazon Basin, LBA studies also included the highly diverse 2 million km^2 savanna region to the south, known locally as the Cerrado, which has undergone more extensive conversion to agriculture than has the Amazon region.

This compilation of 14 papers resulting from LBA-related research covers a broad range of topics with a common theme of coupling land and water processes. How water moves across the landscape and mobilizes dissolved and particulate forms of nutrients and carbon plays a fundamental role in what chemical constituents reach the fluvial system. Hydrologic flowpaths are influenced by land-use change, which in turn affects the characteristics of the aquatic systems, from small streams to large rivers. Papers included in this issue address topics of natural variation of stream chemistry within the Amazon Basin, as well as how land-use change has affected both discharge and water chemistry. Amazonian waters have been broadly shown to be a significant part of the overall basin carbon cycle (Richey et al. 2002), but much more detailed understanding of sources, quality, and magnitude of C inputs to streams needs to be developed, to which this issue contributes. The first two of these papers feature multi-authored synthesis efforts that combine data from several LBA studies across various regions within the Amazon and Cerrado biomes to identify similarities and differences concerning flow paths of water to streams (Neill et al. 2011) and concentration-discharge relationships (Markewitz et al. 2011).

The relative source of water to a stream is the first step in understanding stream chemistry, as rapid surface dominated flowpaths typically bring a different solute load than baseflow. Neill et al. (2011) used an end-member mixing analysis (EMMA) of multiple solutes and end members (groundwater, soil solution, overland flow, throughfall) to examine flowpaths in 10 watersheds of varying size. In forests, overland flow was an important contribution to streamflow in ephemeral streams, but its contribution to streamflow decreased in importance with increasing watershed area. Soil solution contributions were similar across watershed area, while groundwater inputs generally increased in proportion to decreases in overland flow. Most importantly, they found that the relative contribution of overland flow as a source of streamflow was far greater in pasture watersheds than in forest watersheds of comparable size. Results were broadly consistent with results from hydrometric sampling that indicate 17- to 18-fold increase in overland flow for pasture catchments relative to forested catchments. The range in values also suggested that at some sites there were hydrologic flowpaths that were not sampled.

The relationship between stream discharge and concentrations of ions provides an indicator of soil weathering and other terrestrial processes affecting mobilization and transport of solutes. In a synthesis of LBA studies, Markewitz et al. (2011) compiled data from 28 streams in the Amazon and Cerrado regions and applied multilevel, linear regression analyses. In most cases, calcium concentrations were negatively correlated with discharge, indicating highest concentrations under base flow conditions and weathering of primary minerals as the dominant source. Soil class, which is related to lithology, had an important effect on Ca^{2+} concentration, but land use, likely through its effect on runoff concentration and hydrology, had a greater effect on discharge-concentration relationships. Hence the land-use effects on stream chemistry are superimposed over considerable natural variation due to spatial patterns of geology and soil type.

The Madeira River mostly drains a region of Andean carbonate-rich substratum, but there are also some sub-basins with dispersed evaporites. Thus, Leite et al. (2011) found that calcium and bicarbonate were the dominant cation and anion in a study conducted near Porto Velho, with the highest concentrations occurring during the dry season. A novel finding was that bicarbonate was replaced by sulfate as the dominant anion in a year when average discharge was 25% less than normal, indicating inter-annual variation in the relative contribution of source areas. Although no long-term trends have been detected yet for this important tributary of the Amazon, the authors speculate that severe decreases in discharge due to future anthropogenic changes, such as construction of reservoirs or increasing occurrence of drought, may lead to changes in the chemical composition as well as the sediment delivery.

Focusing attention on impacts to N cycling resulting from forest conversion to pasture, Deegan et al. (2011) demonstrate that changes to the aquatic environment follow from land use changes in Rondônia. While forest streams are comprised of run and pool channels with forest leaf detritus, streams draining extensive pastures are grass-filled channels with runs of slow-moving water. This change in channel structure parallels that on the landscape, where land use change alters hydrologic flowpaths and biogeochemical delivery of N to streams. This combination of terrestrial alteration in flowpaths with aquatic changes in stream morphology results in high N retention in small pasture streams, which differs from temperate streams where streams draining agricultural landscapes typically export N. In this study, small forest streams functioned largely as NH_4^+ to NO_3^- transformers and as long-distance conduits for export of inorganic N. Since first and second-order streams make up roughly three-fourths of total stream channel length in Amazon basin watersheds, deforestation impacts on downstream N fluxes is likely widespread.

Continuing the analysis of the effects of land-use on N, Silva et al. (2011) focused on natural, agricultural and urban streams in the Cerrado region. They found streamwater concentrations for most constituents increased as a function of land-use intensity, with streamwater concentrations lowest for undisturbed systems and highest for urban watersheds. Only phosphate was found to not differ by land use, and was observed at low concentrations for all Cerrado watersheds, which is consistent with expectations for a P-limited ecosystem. The increase in NO_3^- for agricultural streams relative to natural streams observed by Silva et al. (2011) is likely due to predominance of row-crop agriculture in these watersheds, which differs from the pasture streams studied by Deegan et al. (2011) for which grass in the stream channels caused a decrease in stream NO_3^- relative to forest streams.

In a second study conducted in the Cerrado, Parron et al. (2011) evaluate N and P fluxes along hydrological flowpaths over three distinct niches along a topographic gradient from well-drained upland soils under woodland savanna vegetation, to a transition vegetative community, to a riparian gallery forest. The gallery forest is underlain by poorly drained Gleysol soils, while the transition and upland areas overlay well drained Latosols (Oxisols). Their results demonstrate the extremely conservative nature of nutrient cycling throughout the Cerrado ecosystem. Among flowpaths, total N as well as all individual N species (NH_4^+, NO_3^-, organic N) had highest volume-weighted concentrations for the litter leachate, irrespective of vegetative community. Results for P paralleled those for N vis-à-vis the flowpaths evaluated.

A less-studied aspect of streams is the input of P resulting from burning. Resende et al. (2011) evaluated the impact of frequent burning on P cycling in the Brazilian Cerrado. They compared a plot that was unburned for 26 years with one that had been burned three times in the 7 years prior to the study. Soil stocks of total P, extractable and occluded P were analyzed to 3 m depth, and compared with fluxes from atmospheric deposition, throughfall, litter leachate and streamwater export. Both inputs from deposition and outputs to the stream were extremely low, indicating a very conservative P cycle. Immobilization of P into microbial biomass was identified as an important buffering mechanism for preventing P losses during rainy season. This P is gradually remineralized and utilized by plants during the growing season. Fire was shown to increase leaching of P from the litter layer to the mineral soil and to deep (1 m) soil layers, where it was retained. Hence, repeated fire may lead to reduced plant-available-P, due to transformation and translocation of organic-P from the litter layer to inorganic-P fixed onto clay minerals in deep soils.

Because deforestation has been more extensive in the Cerrado than in the Amazon forest region, it offers an opportunity to quantify the effects of large scale deforestation on discharge of a major river. One of the more provocative issues about land-use change is to what extent it impacts runoff and sediment generation. Coe et al. (2011) found that the observed decadal mean runoff ratio increased from 22 to 27% of the precipitation and the discharge increased by 25% between the 1970s and 1990 in the Araguaia River. During this period, agricultural expansion increased by 55% in the basin. Numerical model simulations suggested that about 2/3 of the increase was a result of the decrease in evapotranspiration that occurred when native vegetation was replaced with more shallow rooted, less water demanding pastures and crops. The remaining 1/3 of the increase was due to climate variation, predominantly an increase in precipitation. The authors compared their results with independent studies showing similar trends in sediment load and channel morphology changes, and conclude that similar processes might be occurring in other parts of the Cerrado, where increased land demand for expanding agriculture could alter significantly pristine riverine conditions.

How do terrestrial processes translate carbon into streams? Neu et al. (2011) measured C fluxes on the landscape as soil respiration, and fluvial export of dissolved, particulate and gaseous C. They also estimated the CO_2 and CH_4 evasion fluxes from the stream to the atmosphere. Outgassing rates were high for each unit of stream area, however, the stream only occupied a small fraction of the 1,319 ha watershed studied, indicating that the evasion flux was a small component of the watershed C balance. This is largely due to the deep groundwater flows not captured by the stream gage—only 12% of the modeled annual watershed water output occurred as surface flow. Evasion fluxes of CH_4 from streams were in contrast to CH_4 uptake by forest soils. The evasion flux of CH_4 was four times greater than the CO_2 efflux in terms of its global warming potential (GWP). The nature of upland headwater streams as hotspots for CH_4 evasion is a novel finding, as the efflux rate for this tropical forest stream was on the order of those for streams draining boreal peatland.

As noted by Neill et al. (2011), the flowpath that water takes can affect stream chemistry. Johnson et al. (2011) assessed dissolved organic carbon (DOC) quality for a number of hydrologic flowpaths in headwater catchments of the lowland Amazonian forest. They determined the fluorescence index (FI) along with DOC concentrations for throughfall, overland flow, soil leachate and emergent groundwater for the terrestrial environment. Higher FI values are indicative of microbial processing of DOC, with lower values suggesting more labile, terrestrially derived DOC. Flowpaths with longer residence time were found to have higher FI values suggesting more microbially processed DOC. FI for first-order baseflow was found to be strongly seasonal, although the FI values for terrestrial flowpaths were relatively constant. Stormflow FI values exhibited a more "terrestrial" signature compared to baseflow due to contributions of DOC from terrestrial flowpaths during storm events.

Stream chemistry can be affected by not only land-use change but by population centers. Sousa et al. (2011) evaluated fluvial carbon fluxes for the Acre River, an Amazonian river traversing the urbanized area of Rio Branco in Acre state. They found that wet season DOC and dissolved inorganic carbon (DIC) concentrations were similar between areas upstream and downstream of the city. DOC concentrations and fluxes were higher during the rainy season, while the reverse was found for DIC. They investigated tributaries to the Acre with drainage areas ranging from 123 to 7600 km^2, with results similar to the sample points along the Acre River. Despite the lack of wastewater treatment in the urban area, the carbon dynamics are still driven by hydrologic factors rather than by urban waste inputs.

The upper Rio Negro is characterized by extensive interfluvial wetlands, with substantial potential for production of methane. Belger et al. (2011) studied a mosaic of vegetation, dominated by emergent grasses and sedges and patches of shrubs and palms in the region, where they measured diffusive and ebullitive (bubbles) emissions and transport through plant aerenchyma. Methane was consumed in unflooded environments and emitted in flooded environments. The authors show that ebullitive emissions were emitted primarily during falling water periods when hydrostatic pressure at the sediment–water interface declined. The field measurements were scaled up to a 3000 km^2 region using synthetic aperture radar and optical remotely sensed data. Further extrapolation to the area occupied by hydromorphic soils in the upper Negro basin highlighted the importance of this land–water interface as a source of atmospheric greenhouse gases.

Few studies in the Amazonian rivers, or rivers in general, have attempted to quantify the contribution of photochemical transformation of dissolved organic matter (DOM) into DIC and low molecular weight organic acids (LMWOAs) to CO_2 evasion. Remington et al. (2011) conducted photochemical degradation and ^{14}C addition experiments to measure the rates of production and bacterial metabolism of these substrates in the black water Rio Negro and in the white water Rio Solimões during low water. They found that two photochemically produced LMWOAs, acetic and formic acid, may play a significant role in bacterial metabolism in both rivers, although they contributed to only 0.5% of the CO_2 evading from the Rio Negro. Their estimates may be conservative, and more work is needed to quantify the various sources of CO_2 evasion from river surfaces of the Amazon basin.

Yet a broader connection between land, water and the overlying atmosphere is identified by Ramos-da-Silva et al. (2011), through how river corridors influence the development of "cloud streets" (quasi-two-dimensional lines of cumulus clouds, driven by steady easterly trade winds and by moist convection). Based on a series of measurements in the Forest Reserve of Caxiuanã, combined with satellite data and a regional atmospheric modeling system, the authors found that surface heterogeneity is very important for the onset and location of the warm plumes and roll vortices that form the "streets." The onset of convection at the boundaries between the forest and the rivers are the major location for the formation of warm elongated plumes. This process is well represented mainly in the borders of the Xingu River located in the western region of the study domain, and is present throughout the basin. The presence of those cloud streets can affect not only the climate variables, but can also affect the local ecosystem.

The set of papers in this issue covers a diverse set of topics, but several central themes emerge. Flowpaths are clearly important across basin size and structure in determining how water and solutes reach streams. Land-use changes have pronounced impacts on flowpaths, and subsequently, on stream chemistry, from small streams to large rivers (where documentation of effects has been sparse). Carbon is produced and transformed across a broad array of fluvial environments, from small streams to previously unreported interfluvial wetlands. Surface waters are not only driven by, but provide feedback to, the atmosphere. Perhaps the most important message is the spatial and temporal variability; that no one "snapshot" can adequately summarize how the Amazon functions as a regional entity. Overall, these patterns provide insights on how important the coupling of land, water, and the atmosphere are in establishing the basic biogeochemical functioning of the Amazon Basin, and how anthropogenic factors can affect this coupling at a range of spatial and temporal scales.

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