Organic matter and nutrient dynamics in river corridors of the Amazon basin and their response to anthropogenic change

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River corridors of the Amazon basin are a rich and vulnerable part of the basin. They include not only river channels, but also riparian zones, flooded savannas, and extensive floodplains of the large rivers. From a biogeochemical perspective, these extra-channel areas filter material derived from uplands and regulate inputs to the river channels. They are also loci for anaerobic processes and trace gas production. Based on research in the Amazon and elsewhere, deforestation and pasture formation are expected to increase fluxes of sediment, organic matter and nutrients to river corridors. Where the margins of river corridors are intact, their filtering abilities may buffer river channels, and thus downstream reaches, from significant upland inputs. However, river corridors of the Amazon are themselves sites of deforestation and agricultural use, and although it is difficult to predict the biogeochemical impacts of development in these areas, increased downstream fluxes of most constituents are possible. In this paper we examine the potential impacts of land-use change on river corridors of the basin. We then propose a research approach to investigate the course and consequences of these changes. The approach examines river corridors at three scales: Small watershed (< 10 km^2), mesoscale ($\sim 10{,}000$ km^2) and whole basin (7×10^6 km^2). Research sites should be nested, such that the understanding gained at one scale may be translated to the next. Development of quantitative models of river-related processes is advocated, as these models may be linked to similar upland and atmospheric models, thereby facilitating basin-wide analyses of land-use impacts.

Os corredores de rios na Amazônia são ambientes ricos, mas ao mesmo tempo bastante vulneráveis. Eles incluem não somente os canais dos rios, mas também as zonas de matas ciliares, savanas inundadas e a extensa planície de inundação dos grandes rios. Do ponto de vista biogeoquímico, estas áreas fora do canal filtram os materiais derivados da terra firme e regulam sua entrada para os canais de rios. São também locais de intensa atividade de processos anaeróbios e de produção de gases. As pesquisas na Amazônia e outros locais indicam que o desmatamento e formação de pastagens tenderiam a aumentar o fluxo de sedimentos, matéria orgânica e nutrientes para os corredores de rios. Onde as margens permanecem inalteradas, a capacidade filtrante pode proteger os canais dos rios, e portanto os setores rio abaixo, da entrada de materiais da terra firme. Entretanto, os corredores de rios na Amazônia são na realidade sítios que estão sofrendo desmatamento para uso agrícola, e embora seja difícil de prever o impacto biogeoquímico do desenvolvimento de tais áreas, deve ser esperado do aumento nos fluxos de materiais. Neste trabalho, são analisados os impactos potenciais da mudança do uso da terra em corredores de rios da Amazônia. São então propostas atividades de pesquisa para investigar os cursos e conseqüências de tais mudanças. São propostas ações em três escalas: Microbacias (< 10 km^2), mesoescala (~ 10.000 km^2) e macroescala (7×10^6 km^2). Os sítios de pesquisa devem ser hierarquizados de forma que o conhecimento adquirido em um nível, possa ser transmitido para o outro. O desenvolvimento de modelos quantitativos ligados aos processos nos rios é fortemente recomendado, e eles poderão ser acoplados a modelos similares desenvolvidos para a terra firme e atmosfera, facilitando desta maneira a análise do impacto do uso da terra na bacia Amazônica como um todo.

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Humans often transform the relatively complex, intermingled environments of surface water and periodically inundated soils into simple combinations of nonflooded lands and channels of surface water. The land is then used for agriculture and settlements and the channel for water supply and navigation. River corridors in much of the world underwent major modifications by humans before we developed an appreciation of their biogeochemical role and an ability to study their dynamics. Land-use change and river regulation began centuries ago in Europe and Asia and more recently in North America (e.g., References 1,2,3). In contrast, the Amazon is one of the few remaining basins where the watercourses and nearby land have not yet undergone significant human modification.

The Amazon basin is a region defined by its abundance of water. This abundance is evident in the extensive river system which culminates in the world's largest river. In addition, large areas of periodically inundated land are associated with the river system. The floodplain of the Amazon mainstem and primary tributaries cover about 300,000 km^2 (4,5), and riparian zones of small rivers may account for another 1 million km^2 (5). Furthermore, savannas exposed to flooding in the southern, southeastern and northern parts of the Brazilian Amazon and in northeastern Bolivia may account for another 200,000-250,000 km^2 (5). Thus, on the order of 20% of the area of the basin may be subject to periodic saturation or inundation.

The periodically or permanently flooded areas play important roles in the hydrology and biogeochemistry of the basin. The nature of the surface waters and poorly-drained areas is shaped by hydrologic transfers in horizontal and vertical directions, and the biogeochemistry of these areas includes anaerobic reactions such as methanogenesis and denitrification as well as aerobic reactions. In addition these areas form the boundaries between upland areas and open surface water, and they moderate the transfer of water, organic carbon, and nutrients from the uplands to the surface water. The most visible example of the importance of these areas in the Amazon is the floodplain along the mainstem, which has been estimated to produce 5 to 10% of the global flux of CH4 from wetlands to the atmosphere (6).

The Amazon basin is being transformed from a relatively pristine system of forests and savannas to one altered by deforestation and agricultural use (7,8). As discussed in related documents (9,10), land-use patterns such as selective logging, burning, conversion to pasture, and regrowth following abandonment are having profound impacts on the storage of carbon, nutrient dynamics, and fluxes of trace gases in large portions of the basin. These land-use changes may significantly alter the flow of water through the impacted drainage basins, with impacts on the sediment transport and biogeochemistry of the river systems. Poorly drained areas are also subject to direct impacts as humans make use of the resources, such as timber, fish and water, found in these areas.

This synthesis paper reviews two major topics: The nature of the river corridors in the Amazon basin and the existing knowledge of the impacts of human developments, especially deforestation and pasture development, on river corridors. This review attempts to anticipate the specific changes expected in the Amazon, to identify the gaps in knowledge about these changes that could be addressed during future research campaigns, and to outline the possible approaches to filling those gaps.

General functioning of river corridors

The river corridors of a region express the interaction of the hydrology and the land surface, specifically removing the excess water (precipitation minus evapotranspiration) via the lowest elevation pathways (11). The distribution of discharge in streams and rivers is determined by precipitation, transit times and available storage. In small basins, where storage is small and transit times are short, storm events can create temporary conditions of flooding or high water that fall rapidly. In large basins, where rivers receive water from many different areas with varying transit times, runoff is averaged over time, and extended periods of high water and flooding typically occur during times of high precipitation in the basin. Wetlands associated with flowing water, such as river floodplains, may show similar patterns of flooding, whereas wetlands located in areas of low permeability soils or constricted drainage may have hydrologic patterns disconnected from those of flowing water.

Surface water transports dissolved and particulate materials that shape the river system and fuel the biological system. Just as the physical structure of a river channel and floodplain can act as a filter to retain sediments, the biological components can filter the organic matter and nutrients for use in primary production and respiration. The hydrologic regime is the main determinant of the primary producers that flourish in each area of river (12). If the sediment load of the water is high, the turbidity may create low light conditions in which underwater primary productivity is low. Floating macrophytes can abound under such conditions. Phytoplankton, attached algae, and vascular vegetation, including some species of trees, are abundant in various habitats of riverine corridors. If the flooding follows a seasonal pattern, annual herbaceous vegetation may develop in open areas as floods recede, to be replaced by aquatic macrophytes or algae as floods invade. Vascular plants also grow in moist soils of riparian zones and wetlands and can colonize new areas of deposition. Because of the presence of water, primary production may continue in these zones after it has ceased in the uplands due to seasonal drought. Within the river corridor, different primary producers may achieve their peak of production at different stages of the hydrograph.

The organic matter from the primary producers and the organic matter transported from the uplands are fuel for consumers in the water, sediments and soil. The organic matter may be consumed near its place of production or transported down slope or downstream before being consumed. Because oxygen transport is reduced in water, oxygen availability can be become limited in many areas in these settings, leading to the development of anaerobic conditions. Most freshwater have low concentrations of electron acceptors such as nitrate and sulfate, so fermentation and methanogenesis are the main anaerobic means of organic-matter degradation. The distribution of aerobic and anaerobic conditions in these areas determines the relative production of CO_2 and CH_4 and the extent of CH_4 oxidation. These degradation reactions also involve the mineralization of organic N, with the potential for production of N trace gases. Alternations of nonflooding and flooding conditions can create conditions for the sequential mineralization of organic N, aerobic nitrification, and anaerobic denitrification. These steps produce N2, N2O and NOx trace gases and remove nitrogen from cycling within an ecosystem.

Researchers have attempted to describe the biogeochemical dynamics of river corridors with conceptual models. The River Continuum Model describes river corridors as systems in which river properties should vary systematically downstream as processes affecting the interactions of flowing water with the landscape give way to within-river transport and processing (13,14,15). Junk et al (16) have proposed the Flood Pulse model to recognize that, in rivers with large floodplains, significant landscape interactions continue even in very large rivers. Other researchers have recognized that the chemical signatures of riverine materials can be tied to landscape-related processes such as chemical weathering and nutrient retention by local vegetation (17). Ideally the hydrologic and chemical signatures of rivers can be used to understand different drainage basin source regions and to understand natural or anthropogenic perturbations over time (18). Rivers should respond with differing magnitudes and lags to perturbations depending on the processes involved and the downstream transfer rates of their characteristic products.

River corridors in the Amazon basin

The Amazon drainage basin (Fig. 1) is characterized by a western rim of very high relief in the Andes and sub-Andean trough that rapidly grades into regions of low relief in the shield areas and the alluvial plains. The central basin and the corridor to the Atlantic are composed of sediments from these formations as well as marine deposits (19). The geologic stability of most of the basin and the high amounts of rainfall have lead to the development of a low-gradient topography and highly weathered soils, usually oxisols and ultisols, in the region beyond the Andes. Phosphorus is often the limiting nutrient for the terrestrial vegetation, because it is present in forms unavailable to organisms (20). The chemistry and sediment load of the basin's surface waters are determined by the soils and relief of the source regions. The river corridors in the Amazon landscape can be roughly grouped into three types: The larger rivers and their floodplains, the small streams and rivers and their riparian zones, and the periodically flooded savannas.

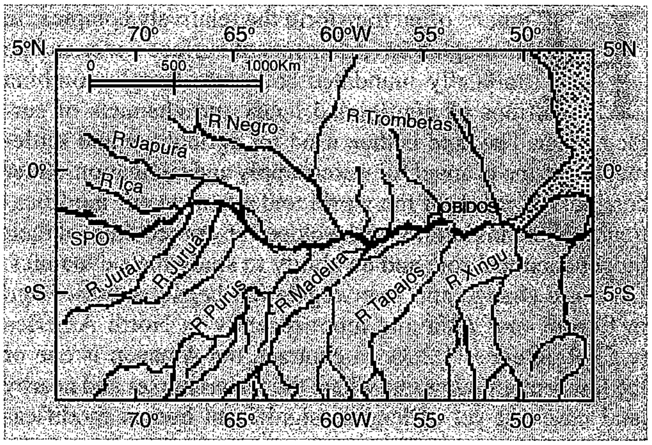

Figure 1. Schematic of the central Amazon basin, showing the mainstem and its major tributaries.

Basin-scale drainage system

Surface water flow in the Amazon basin is channeled through an extensive river network to the mainstem channel, which flows eastward from the Peru-Brazil border to the Atlantic Ocean (see Fig. 1). At Óbidos, the easternmost gauging station on the mainstem, the accumulated upstream drainage area is 4.2 x 10^6 km^2, and the mean annual discharge is approximately 160,000 m^3/s (21). Incorporating the discharges of the Tapajós, Xingu and Tocantins rivers, the total mean annual discharge to the Atlantic is approximately 210,000 m^3/s. The annual hydrograph of the mainstem is damped, in part due to the temporal offset of peak flows coming from its major tributaries. The peak flows from the northern and southern tributaries are typically three months out of phase as a result of the seasonal differences in precipitation. The predominant interannual variability in mainstem discharge occurs on a 2 to 3 year time scale, and oscillations in the hydrograph are coupled to the El Niño-Southern Oscillation cycle (22). Major mainstem tributaries (with mean annual discharges) include the Içá (6,000 m^3/s) and Japurá (15,000 m^3/s), which originate in the Andes and cross the lowland plains to the mainstem, and the Jutaí (4,000 m^3/s), Juruá (5,000 m^3/s), and Purús (12,000 m^3/s), which drain the sub-Andean trough and the central plain. The Rio Negro (25,000 m^3/s) drains primarily the campina forests of the "planalto das Guianas", while its major tributary, the Rio Branco, drains a drier savanna region. The Rio Madeira (30,000 m^3/s) originates in the Bolivian Andes and then passes across the "planalto brasileiro" and the central plain. Flow in the mainstem at the Peru-Brazil border is composed primarily of Andean water, with average minimum and maximum discharges of 20,000 and 60,000 m^3/s, respectively.

The rivers with predominant Andean origin, such as the mainstem and the Rio Madeira, are white-water rivers with high sediment concentrations. They drain relatively unweathered soils and geologic formations in areas with "weathering-limited" denudation (23), i.e., transport processes are more rapid than weathering processes. Because the transported materials are rich in soluble components, the dissolved inorganic loads of these waters are high. The Andes contribute over 90% of the sediment load of the Amazon to the ocean, estimated at 1.2 billion ton/yr (24).

The black-water and clear-water rivers of the basin lack Andean headwaters and drain older, more weathered soils on lower relief surfaces. These areas are said to have "transport-limited" denudation (23), and the resulting waters have very low suspended sediment concentrations and are relatively transparent. Black-water rivers such as the Rio Negro are usually tea-colored in appearance due to a high load of organic acids, which are derived from white-sand soils (spodosols) in their catchments (25).

The biogeochemistry of the mainstem river has received the most attention and serves as a useful example of the dynamics of large white-water rivers in the basin. As part of the carbon in the Amazon River Experiment (CAMREX), Richey and coworkers at the University of Washington, the Instituto Nacional de Pesquisas da Amazônia (INPA), and the Centro de Energia Nuclear na Agricultura (CENA) have been investigating the mainstem since the early 1980's. Their sampling approach utilizes a series of monitoring stations along the mainstem and at the mouths of major tributaries (21). These stations serve as integrators of upstream processes and define inputs to downstream reaches and, ultimately, to the ocean (26). The challenge in this approach is to explain the measured distributions of composition and flow at the monitored stations in terms of upstream processes, including processes on land.

The metabolic activities of the mainstem Amazon are limited to heterotrophy by the high turbidity of the water (27), although the dissolved oxygen of the river still carries the imprint of floodplain or tributary photosynthesis in its $\delta^{18}O$ content (28). Bacterial metabolism is the primary energy flow pathway and appears to be substrate-starved (26,29). Within-river respiration appears to be largely at the expense of a limited pool of moderately reactive compounds dispersed among highly degraded dissolved and particulate forms (30). Gas exchange is in quasi-steady state, with the outward flux of respiration-produced CO_2 roughly equal to the inward flux of atmospheric O_2 (31). The mainstem also emits some methane derived from floodplain sources (32).

In addition to hosting metabolic activities, the Amazon serves as a transporter of huge amounts of organic C and nutrients. The Amazon river delivers a large load of organic matter and nutrients to the ocean, on the order of 30 Tg ton C/yr, 2.8 Tg N/yr and 1 Tg P/yr (18). The organic geochemical composition of suspended sediments represents a sequence of processes originating with the fixation of carbon primarily on land that has been subsequently degraded and mobilized. A hypothetical sequence of processes that may control the transfer of terrestrial production to aquatic systems and to the atmosphere is shown in Figure 2. Coarse particulate organic material (CPOM) carried by the mainstem appears to consist of relatively fresh tree leaves, while both the fine particulate organic material (FPOM) and dissolved organic material (DOM) fractions are highly degraded (30). FPOM is richer in nitrogen than DOM, however, and contains five to ten times more total amino acids (30). Increased concentrations of nitrogen in FPOM fit a scenario in which leaf degradation products that are richer in N are selectively partitioned onto negatively charged particles (as nitrogen imparts a local positive charge to organic molecules). Carbon isotope evidence suggests that the organic matter carried by the river includes more floodplain sources as it moves downstream (33). Measurements of ^{14}C age indicate that FPOM has the longest maximum residence time in the basin and thus moves most slowly through the drainage network (34). The ^{14}C signature of bulk DOM is close to that of the modern atmospheric, which suggests that its diagenesis and transport times are surprisingly short.

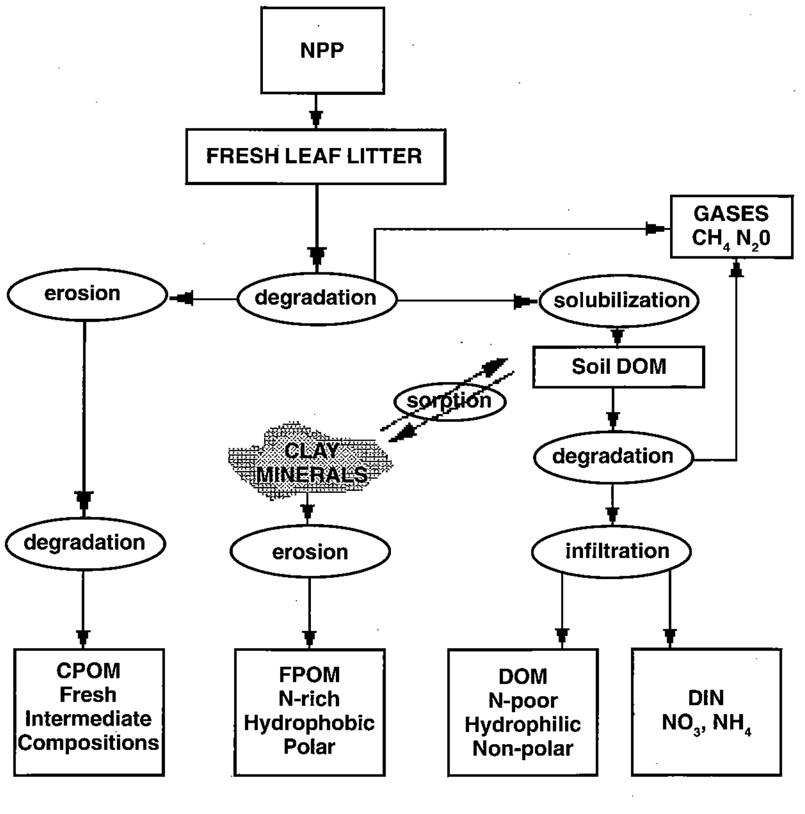

Figure 2. Conceptual model of the production of terrestrial organic matter and the pathways for its degradation and partitioning, including its mobilization into rivers and the atmosphere.

Floodplains of the mainstem and large tributaries

The Amazon river and most of its large tributaries have developed extensive floodplains, which are integral parts of the river systems (Fig. 3). Floodwaters inundate the floodplains each year via an extensive network of drainage channels called "paranás". The floodwaters of white-water rivers carry sediment that can be deposited and re-eroded on the floodplain; the black and clear water rivers carry much less sediment and may have more stable floodplains. The floodplain of the mainstem illustrates the possible geomorphological patterns due to differing geologic regimes, ranging from a floodplain with intricate scroll-bar features and long, narrow lakes that is associated with a meandering river near the Peruvian border in Brazil to a narrower floodplain around a constrained river channel upstream of Manaus (35). The floodplains include areas of seasonal inundation and permanent lakes. Approximately 10,000 km^2 of the mainstem floodplain is covered by thousands of permanent lakes that average less than 0.5 km^2 in area at low water (4). The lakes are typically 6 to 8 m deep at high-water, but their depths decrease to 1 to 2 m as the river falls and land is re-exposed. Numerous smaller tributaries drain exclusively lowland regions into the main channel or into the floodplain, while large "paranás" act as diversion canals between the main channel, floodplain, and tributaries, with the flow direction often depending on river stage.

Along the mainstem Amazon, flooding follows a three-stage pattern, with water entering the floodplain first through deep breaks in the levees that define the main channel, then through shallower levee breaks, and finally by overtopping the levees (35). Floodplain exchange is a significant component of the water budget of the mainstem; these flows comprise up to 30% of the flow in the upper part of the reach and cumulatively about 25% of the flow at Óbidos, depending on the season (36). The floodplain also acts as a major storage reservoir for sediments that are carried by the river (37). During high-water portions of the hydrograph, large amounts of suspended sediment accompany floodwaters onto the floodplain. Field measurements indicated that over 80% of this suspended sediment is then deposited on the floodplain surface (38). Conversely, substantial amounts of sediment enter the mainstem via bank erosion. Estimates of the contribution of floodplain soils and sediment to the mainstem flow indicate that approximately 1.5 billion ton of sediment are eroded annually. Conservatively, these values indicate that the exchange of bank materials at least equals the discharge of sediment passing Óbidos annually, estimated at 1.2 billion tons. Mineralogy and ^{14}C data suggest that a typical suspended particle passes through the floodplain several times and that, given the pattern of channel migration, the floodplain in most reaches is recycled over a few thousand years.

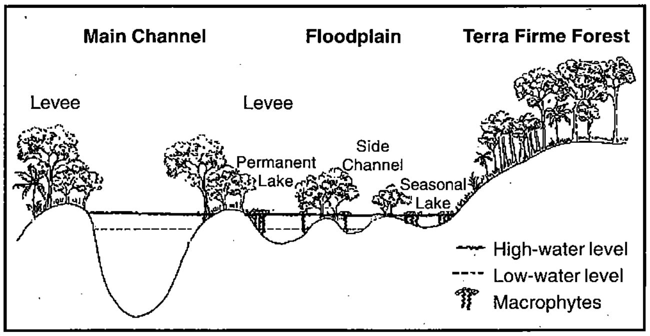

Figure 3. Idealized cross-section of the floodplain of the Amazon river, showing major floodplain environments and vegetation, including the areas of growth of aquatic macrophytes during annual flooding.

Biological activity on the floodplains is tied to the cycle of flooding, with productivity alternating between plants that flourish during the floods and plants that tolerate the floods but are most productive when not inundated. The main communities on the floodplains are forests of flood-tolerant trees, nonforested lands that alternate between grasses during low-water and floating aquatic vascular plants during high-water, and open-water lakes that expand as the floodwaters rise (see Fig. 3) (5). The extent of the aquatic vascular plants is much less on the clear-water and black-water rivers than on the white-water rivers, and in general, biological activity is greatest on the floodplains of the white-water rivers. The trees on the floodplain grow mostly during low water and many drop their leaves during inundation (39). The sources of water in floodplain lakes vary in their nutrient content, and the relative contributions of these sources varies among the lakes and among the seasons (40,41,42). Phytoplankton in the lakes and macrophytes on the edges of the lakes flourish after river water enters the floodplain and supplies nutrients for growth (40,43). Phytoplankton communities in various floodplain lakes have been found to be limited by N (44,45) and by both N and P (46). Inorganic turbidity regulates the ability of attached algae to utilize nutrients supplied by river water (47). The productivity of the floodplains can be quite high, on the order of 25 ton C/ha/yr in the herbaceous communities (48), 16 t/ha/yr (49) in the floodplain forest, and 3 t/ha/y in the phytoplankton community of a lake (50).

Much of the organic matter produced on the floodplain is also degraded there. Decomposition during the inundation phases includes a significant anaerobic component. For instance, floodplain lakes are often stratified with an anoxic lower layer (51), and low oxygen conditions also develop in the waters beneath flooded forests and macrophytes (52). Methane fluxes have been measured during inundation in the major vegetation communities on the Amazon floodplain (53,54,55,56). The magnitude of methane production from the floodplains may be as much as 5-10% of the total global CH_4 flux from wetlands (55). The majority of the flux is carried by ebullition, so that the areas of methane oxidation in the waters are bypassed.

Streams and small rivers

Large rivers are the characteristic feature of the Amazon landscape, but these large rivers owe their flow and chemical loads to a much denser network of small rivers and streams. In an area near Manaus, the stream density is approximately 2 km/km^2 (57), and the combined area of the streams and riparian areas in the basin has been estimated at close to 1 million km² (5). Small streams in the non-Andean Amazon have only been investigated in detail in the vicinity of Manaus. Annual discharge hydrographs for these streams display a monomodal baseline, related to seasonal fluctuations in precipitation, as well as a superimposed polymodal structure produced by event-based peaks in discharge (58,59). The hydrology of the small streams is strongly influenced by the surrounding land surface as well as by the upstream reaches. Most of the flow is fed by ground-water discharges (59), while storm flow occurs as saturation overland flow originating in near-saturation riparian soils (59,60).

In the relatively low-gradient terrain of the Brazilian Amazon, streams follow slow and meandering courses through flat-bottomed valleys. The streams are often bounded by riparian forests whose elevation is similar to the streams and lower than that of the surrounding forests or grasslands (Fig. 4). Although sediment loads in streams and small rivers of the Brazilian Amazon have not been measured, low river gradients suggest low sediment loads. The chemistry of the streams falls within the general categories of black and clear waters (61,62), varying according to the geologic characteristics of their watersheds. Lesack (63) found that inputs of major cations, anions, and nutrients to a central Amazonian catchment were significantly increased in storm flow, making the riparian zone a source of these ions during storm events.

In the central Amazon, riparian soils are sites of denitrification and N_2O production. In a small catchment north of Manaus, NO_3^- in ground water exiting the upland was rapidly consumed upon entering the riparian zone, probably due to denitrification in the low-oxygen riparian ground water (64). Ammonium replaced NO_3^- as the dominant inorganic N species in riparian ground water, but it too was consumed as riparian ground water passed into the stream channel, probably due to a coupling of nitrification and denitrification. Analyses of δ ^{15}N of inorganic N in ground water and stream water suggested that stream inorganic N derived predominantly from the mineralization of organic N in the stream channel (65). Livingston et al (66) measured N_2O fluxes and N mineralization rates in soils from this site. They found N_2O fluxes to be of similar magnitude from both upland and riparian soils, although reported rates of N mineralization in upland soils were three to four times higher than those in the riparian zone.

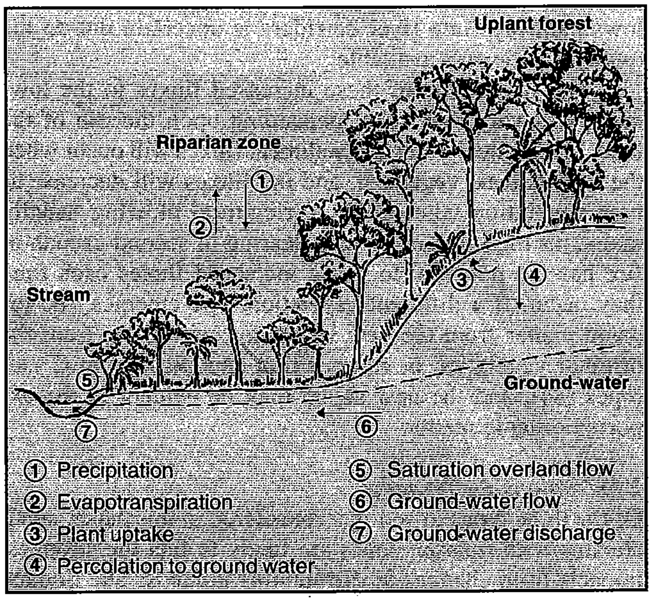

***Figure 4.** Idealized cross-section of a upland-riparian-stream system. The significant pathways for the flow of water and water-vapor are indicated.*

Flooded savannas

At the northern and southern edges of the basin, climatic and soil conditions support savanna vegetation. Large portions of these savannas experience significant flooding during the annual rainy season and thus behave as seasonal wetlands (5). Streams draining the savannas are generally classified as clear water. Although the vegetation of these areas has been studied and described (67), the surface-water environments have received little attention. The areas are dispersed geographically and vary in their topography and soil conditions.

Primary production in the savannas is mostly owed to the perennial grasses that cover most of the land. The production of the grasses peaks at the beginning and end of the rainy season. Near the streams and lakes, forests often develop that play similar roles to that of the forested riparian zones and floodplains described above (68). In addition, the lakes and unshaded portions of the streams can support the growth of aquatic vascular plants. The soil in the savannas is generally low in nutrients, although Sarmiento (67) reports that N fixation is high in the savannas relative to the forests. The savannas in many areas experience recurring fires. Trace gas production has not been studied in Amazonian savannas, but high production rates of methane have been measured in the Pantanal (69), a similar savanna wetland located directly to the southwest of the Amazon.

Impact of anthropogenic change on river corridors

As development of the Amazon basin proceeds (10), the river corridors and wetlands are affected by changes occurring in the surrounding uplands and by alterations within their borders. Although certain areas could be experiencing both types of changes at once, it is simpler in this review to consider the impacts separately. Because most of the research in the Amazon has focused on characterization of the natural systems, hypotheses about expected changes are constructed in part from research done in areas outside the basin.

Upland development and potential lowland responses

Mechanisms of change

The most general result of development of the uplands is the removal or alterations of the vegetative cover, often accompanied by construction of roads for access. In the forested portions of the basin, the first step in development is deforestation. The least destructive actions occur under selective logging, in which only the valuable timber trees are removed and the forest is allowed to regrow (10). Full deforestation may be carried out for logging purposes alone or more often for logging combined with clearing the land for agricultural uses. If the clearing was an initial step in agricultural use, the debris of the remaining trees may be burned to release nutrients. Cattle ranching is the most common use of cleared land in the Amazon and is carried out by large land owners, while smaller land owners may practice slash and burn agriculture in more limited areas (9). Much of the savanna areas within the basin have been converted into pasture. If farmland or pasture is abandoned, as often happens as productivity falls, second-growth vegetation develops. Nepstad et al (70) have noted that these areas of second growth are increasingly being cleared for more intensive pasture formation. These changes in the vegetative cover often increase the likelihood of fire. These various uses, from selective and full logging to pasture and agricultural use, differ in the types of vegetation that replace the original cover and in the times, if any, in which bare soil is exposed.

Changes in the uplands can affect the lower-lying river corridors by altering the fluxes of water, sediment, and biological materials transferred to them (Fig. 5). In most cases these fluxes will increase initially and perhaps in the long term as well. Increases in stream runoff have been observed in many locations after deforestation (71,72). The transpiration of new vegetation is usually less than that of the original (73) and the water-holding capacity of the soil may decrease as well. As vegetation and soil properties change, the pathway of runoff can also change. The removal of the tree canopy and the decay of the tree roots can create a soil surface more prone to overland flow and erosion during rainfall. As noted in several Amazon studies (74,75,76), the mechanical actions of deforestation and pasture use often reduce the infiltration capacity of the soil, increasing the amount of runoff as overland flow. In the central Amazon, the remaining microtopography may still capture rainfall after a short period of overland flow (77), but over time bulldozers or cattle may smooth the microtopography, generating more overland flow. Roads are an extreme example of compacted, low-infiltration surfaces that encourage overland flow (78).

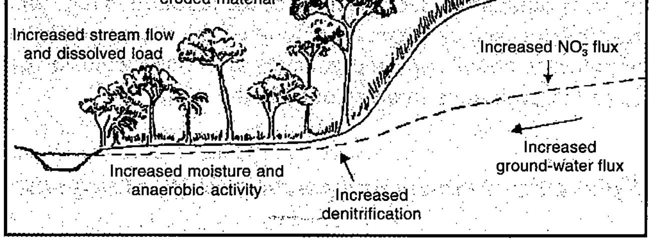

Figure 5. Schematic of deforested upland beside intact riparian zone and stream. Expected changes in lowlands are indicated, as well as relevant changes in uplands.

The pathway taken by the increased runoff affects fluxes of other materials. If the runoff follows overland pathways, it can transport particulate materials as well as dissolved. In an experimental plot in the central Amazon, sediment erosion increased from the rooted zone following deforestation (76). In the US, sediment losses often increase under cattle grazing (79,80). As observed by E Safran in the central Amazon, the potential for sediment movement seems to be related to soil type, with the ultisols being more vulnerable than the oxisols due to microaggregate formation in oxisols (81).

In the short term, the destruction of the original vegetation increases the availability of organic matter and nutrients for degradation and export. These releases of organic matter and nutrients are especially significant in the Amazon, where so much of the ecosystem's nutrients are held in the vegetation and the uppermost organic soil rather than in the mineral soil (82). Following cutting and burning of a deforested experimental plot in the Amazon, concentrations of nitrogen species and major cations increased in soil solution and groundwater relative to a control plot (76). Concentrations of Na^+, K^+, SO_4^{2-} and Cl^- in soil solutions in particular increased more than ten-fold following burning. Leaching of nitrogen in particular is often noted in deforested plots. The nitrogen originally held in organic matter may be exported as crops, leached as dissolved organic nitrogen, or mineralized. Following clearing and burning, nitrogen losses from some tropical sites have been estimated at as much as 1400 kg/ha from the upper 30 cm of soil (73). Nitrogen that is mineralized to NO_3^- is especially mobile in most soils. Nitrate losses three to fifty times higher than that of control sites have been observed in many temperate areas following deforestation (83). As is the case for other elements, the exact proportion of total nitrogen lost that follows pathways into river corridors is uncertain due to the multiple pathways available.

The magnitude of these increased fluxes to the lowlands will vary over time, depending upon the use of the land. The highest water and sediment fluxes will occur when the land is least vegetated, and the fluxes will decrease as new vegetation takes hold. Agricultural plowing usually maintains high flux rates, and clearing of second growth or fire has the potential to cause increased fluxes each time they occur. If a different vegetation type emerges, the organic matter from the new vegetation will differ from the original vegetation in composition and perhaps in C isotopes (84), and the new signal may be evident in the exported organic matter.

Expectations for response

Of the three types of settings considered in this paper, small streams with riparian zones are likely to feel the strongest impacts from changes in surrounding uplands. The flooded savannas do not have an identified upland zone that acts as a source area, and the larger rivers are more connected to the uplands through their upstream drainage network than at the river's margins.

Although little work has been done on the response of Amazonian riparian and stream systems to change in the uplands, the role of riparian zones in buffering local and downstream rivers from impacts in the surrounding areas has received significant attention elsewhere in the last two decades. In many cases, a healthy, intact riparian zone can process the increased fluxes from the upland via groundwater and eroded materials, thus dampening the signal seen in the rivers (see Fig. 5) (85). If overland flow off the hillslopes is occurring, the relatively flat riparian zones can slow the flow, causing it to infiltrate. Sediments and organic particles carried in the flow will likewise be slowed and deposited (86). The increased fluxes of organic matter and NO_3^- in the groundwater may be consumed in aerobic or anaerobic processes, including methanogenesis and denitrification. For instance, the denitrifying capabilities of riparian zones have been found to protect streams from inputs of fertilizer N (87,88). Riparian zones can also decrease fluxes by taking up organic matter and nutrients into biomass and sediments (87).

The filtering of increased fluxes of materials by the riparian zone probably entails some change in functioning within the zone. Increased groundwater flow and overland runoff may increase the area of periodic inundation in a basin. A significant rise in the water table may stress the rooted vegetation of the riparian zones. Increased moisture in these areas may also decrease the availability of O_2 and possibly slow decomposition but increasing the percentage of methane produced. More sediments may alter topography and smother vegetation. Local streams will probably still receive increased fluxes when compared to undisturbed conditions. Following burning of a deforested experimental plot in the central Amazon, concentrations of most solutes, including NO_3^-, NH_4^+, SO_4 and Al, rose above control levels throughout most of the post-cut sampling period in stream water even though a riparian buffer had been left uncut from the original vegetation. The increased baseflow could supplement stormflow enough to increase the movement of sediments and organic particles during storms.

Expected impacts of direct alteration in river corridors

Intact riparian zones and floodplains could buffer the impact of land-use changes in the uplands on the surface water and downstream environments. However, the river corridors of the Amazon are themselves undergoing changes that will affect their nutrient dynamics and buffering ability (89). The floodplains of the Amazon and some of its major tributaries support important fisheries and are a source of easily accessed timber (90). Over 50% of the forests on the floodplain of the eastern mainstem Amazon has undergone deforestation (91,92). The fertile floodplain soils of white-water rivers are used during the dry season for agriculture and cattle ranching (93). The riparian areas of small streams are often subjected to the same deforestation and agricultural practices as the surrounding upland areas, and road construction may block the paths of the streams themselves. Much of the flood savanna is used as cattle pasture in Bolivia, which may entail the replacement of native grasses with specific pasture grasses.

As in the uplands, development of the low-lying areas largely involves the removal or destruction of the original vegetation and replacement by another type. The general responses of these systems are initial losses of water and materials and decreased retention or filtering of water and materials from other areas (Fig. 6). Because development is likely to alter the fundamental properties of the ecosystems in these areas, the impacts of these alterations are more difficult to foresee than the indirect impacts of changes in the uplands.

Changes in the vegetative cover of the riparian zones and floodplains will change the movement of water across these areas. With vegetation removal, transpiration will decrease but evaporation from surface water and moist soils may increase if they are now exposed to more solar radiation. Sharper peaks in stormflow are possible as the retaining vegetation in the lowlands is removed. Any filling in of low-lying areas will reduce the area available for surface water flow and encourage higher flow rates. An overlooked impact of development on hydrology occurs during road construction. Near Manaus, for instance, roads have been built across small streams without building culverts for drainage. Large areas of standing water have accumulated on the upstream sides of these roads, causing the death of the nonriparian forest and turning formerly upland areas into wetlands (94). Road construction in the Bolivian savannas has also created some year-round wetlands, in trenches dug during road construction in order to obtain soil for elevating the roads.

Removal of the vegetative cover makes sediments and organic particles more available. The removal of forests from riparian zones and floodplains will decrease the roughness of the surfaces, allowing less impeded flow. Since most sediment movement occurs during storm flow, expected increases in the magnitude of stormflow will allow increased sediment transport. Even if grasses and trees regrow, the roots of the larger trees will decay and no longer hold soil. Cattle only exacerbate these conditions by trampling stream banks and slowing the regrowth

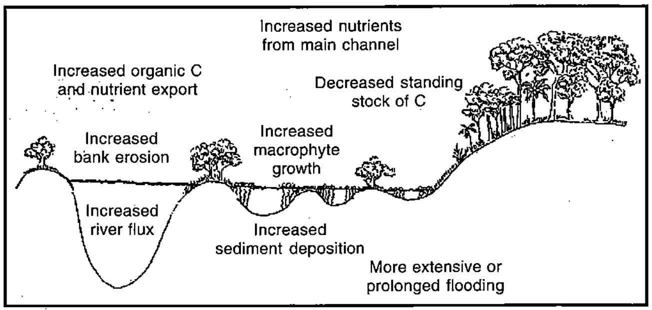

Figure 6. Schematic of deforested floodplain and indications of possible changes due to disturbance in the local area as well as upstream.

of vegetation. In temperate streams, debris dams, which are trees that have fallen across streams and behind which material accumulates, play a large role in sediment and organic-matter transport (95). Deforestation removes the source of these dams, so they are not replaced when older ones decay (96,97). The importance of debris dams in the Amazon basin is not clear, given the low gradients of the rivers and the fast decay times of organic matter.

Alterations in the river corridors affect both the primary production and degradation aspects of biological functioning. As development proceeds, especially the formation of pastures, the expected changes in vegetation in the river corridors are generally shifts from trees to herbaceous plants. This switch decreases the production of certain types of organic matter, such as trees' leaves and trunks, and increases inputs of herbaceous material, from pasture or second-growth vegetation (98). The annual pattern of production may also change, especially in seasonally flooded areas. In some cases, increased moisture in the soil may inhibit the growth of trees. In other cases compaction of soil or loss of organic matter may lower the field capacity of the soil and thus the water stored in the soil for use during droughts may also be less, stressing plants during the dry season. In surface-water environments, algal and macrophyte productivity may increase if forest canopy is removed and more radiation reaches the water (99) or if additional nutrients are released from decaying organic matter. Algal production could decrease if increased sediment loads from disturbed areas increase the turbidity of the water and thus lower the availability of light.

Following disturbance, the interaction of the changes in hydrology and in primary production can determine the setting for decomposition. The initial impacts following deforestation include a release of the materials held in the vegetation debris. The decomposition pathway of this material will depend in part on the availability of O_2, which itself is determined by the moisture status. On one hand, increased storm flows and decreased transpiration may produce longer and more extensive flooding in some areas, thus increasing the amount of time during which anaerobic decomposition occurs and encouraging CH_4 production and denitrification. Likewise, if new wetlands are created by road blockages, CH_4 fluxes are expected to be high. On the other hand, decreased retention of moisture or increased drying may create more aerobic conditions, possibly leading to the decomposition of older organic matter stored in the exposed soils as well. These conditions may also enhance decomposition of organic matter accumulated over long periods in the soil. As a complicating factor, organic matter may also be lost from the systems at relatively high rates before it can undergo decomposition, as noted in watersheds where streams were cleared of debris (100,101).

Because the areas bordering surface water are being disturbed, the surface water environments are more likely to be affected than with only upland disturbance. Without their filtering system, the rivers may carry larger loads of organic carbon and nutrients to downstream areas. One possibility is the enhancement of primary production downstream due to the increased nutrient loads.

Possible impacts of long-term and regional changes

The impacts of development in the Amazon basin will probably be noticeable in different types of river corridors over different time scales. The riparian zones of small streams, the river corridors most intimately connected to the land, will probably experience changes soon after the upland changes, as will those riparian zones and floodplains that are directly altered. Larger rivers and floodplains downstream of developed areas will probably respond more slowly as the proportion of the upstream basin that is developed increases. At some time, the fluxes exported from the basin may be altered enough that changes are observed in the Amazon's estuary, where riverine nutrients are consumed in production and organic matter on riverine sediments is degraded (102).

As more money and people are poured into development of the Amazon basin, the pathway of development itself may change. The Amazon may come to resemble many of the world's river basins that have drainage networks that have been channelized and cut off from the floodplains, agricultural lands that have been "reclaimed" from wetlands, and large loads of fertilizers and anthropogenic chemicals in the surface water. In the Amazon the most likely change is an increase in intensive agriculture. High-phosphate fertilizers are already used to reclaim abandoned pastures. The use of fertilizers in areas near the streams could add nutrients and increase productivity in local surface water. The use of fertilizers and pesticides on the floodplains of white-water rivers, the best agricultural land in the basin, would add chemicals directly into those ecosystems. In addition, the extent of river regulation may increase. The drainage of areas such as the floodplains is possible, which would decrease the wetland character and decrease methane production. Although dams are not seriously planned for the mainstem Amazon, flood control and hydroelectric structures are possible on medium-sized rivers (103,104), and dams may be installed for irrigation in the drier areas. If urbanization and industrialization increases in the basin, the input of industrial and domestic wastes to surface water will increase.

Summary and research questions

In order to understand the responses of organic matter and nutrient cycles in Amazonian ecosystems to forest conversion, the issues raised above must be addressed by future research campaigns. Understanding these responses is an essential step in assessing their impact on the quality of the natural environment, the health of the human population, and the chemical composition of the atmosphere. In the area of river corridors and surface water chemistry, the broadest questions can be posed as:

- What are the changes in the pathways, fluxes and processing of organic matter and nutrients through river corridors?
- How can these changes be described as a function of

original landscape characteristics and imposed land use?
- How much change is required to create a signal larger than natural variability at various scales, and how far downstream will disturbance signals persist?
- Which river corridors of the basin are most susceptible to damage from land-use change?

As reviewed above, the possible responses of Amazon rivers and associated areas to land-use change include the following:

- Increased fluxes of water, sediment, organic matter and nutrients from uplands, including an initial pulse of composition and nutrient release, and perhaps changes in the nature of organic matter transferred
- Changes in the hydrologic flow paths such as an increase in overland flow
- More extreme hydrographs because of less retention and transpiration on land surfaces, at least initially
- Changes in the patterns and frequency of flooding
- More sediment movement within channels, possibly changing the character of some rivers from clear or black to white
- Changes in the relative production of CO_2 and CH_4 depending upon the balance between changes in hydrology and organic-matter input
- Changes in primary production in surface water due to increased turbidity or additional N and P

Investigations designed to address the effects of land-use change in the Amazon may look for patterns observed in other systems, such as the buffering role of riparian zones, but these investigations must also ask questions that are unique to the Amazon setting. A particularly important aspect of the Amazon basin is the broad spectrum of scales encountered within its margins. The impacts may be expressed differently in different parts of the basin due to differences in soil type or relief. Hence, research strategies capable of addressing the questions posed above must cross multiple scales, from that of a single hillslope to that of the entire 7 x 10^6 km^2 basin. The following discussion outlines the types of experimental approaches that may be undertaken to proceed from the study of detailed land/stream interactions at one site to the study of larger rivers responding to the inputs from land surfaces spanning a large portion of the Amazon basin. These approaches will be most effective if research sites of different spatial extents are nested within each other. At each scale, approaches must include provisions to characterize natural variability. An important tool is the use of specialized tracers such as isotopes and specific organic molecular biomarkers in addition to "bulk" chemical measurements, since these biomarkers retain information about specific processes that influence the concentrations and fluxes exported by rivers.

Detailed experiments conducted at individual field sites are critical for developing a process-based understanding of the responses of Amazon river corridors to changes in land use. These experiments could be used to investigate the natural dynamics of Amazon river corridors that are not understood, such as limiting nutrients in Amazonian surface waters, the chemistry of surface water in the flooded savanna, or the natural CH_4 production in riparian zones and small streams. Improved understanding is also needed of the process of organic matter movement from the uplands into lowlands and the variables which control CH_4 generation (105). These detailed experiments should be conducted within larger study areas so that the understanding derived from these experiments can be translated directly into hydrologic and biogeochemical models.

Small watershed studies are as important to the issue of horizontal transport as are instrumented towers to vertical fluxes. Only in small basins can the export of water, sediments, nutrients and organic matter be rigorously quantified and models of land-use change impacts will require such measurements. While some signals can be detected downstream, much of the biogeochemical activity related to land use will take place in low-order streams and their riparian zones close to the site of the disturbance. A research program addressing land-use change across the basin should include small watershed studies in each major region of the basin. In an intensive study of two basins (disturbed vs undisturbed), monitoring can determine the water balance and flow paths of solutes and can allow the assessment of how fluxes and processes might change under land-use change. These measurements in small watersheds yield essential boundary conditions for larger modeling efforts. As a complement to small watershed budget studies, we envision the use of hydrologic modeling coupled with models of how nutrients move through the soil environments, both to the atmosphere and to the streams.

An important objective in studying the Amazon basin is to understand the processes controlling the distribution of water and the influence of this distribution on ecological and biogeochemical processes at the so-called mesoscale (~ 10,000 km^2), which is roughly the scale desired for linking to general circulation models. In basins of this scale, in-channel and downstream processes begin to affect the signal imparted by upstream disturbances, and research at this scale can ask: "How persistent is the signal from local changes?" Although the paired-basin approach can also be used at this scale, instrumentation and measurements cannot be used to track all individual processes and pathways. Instead, approaches must be used to integrate information across an area. Element budgets of mesoscale regions can be constructed and compared to fluxes of gases, as measured by aircraft or tower arrays. Mesoscale understanding needs to be distributed between different land covers and land uses, climatological regimes, and topographic settings, including the Andean source areas.

Selection of mesoscale drainage basins represents a series of tradeoffs in terms of basin size, characteristic land forms, and especially, logistics. Finding paired basins in which one is forested and the other deforested becomes much more difficult when desired basins are on the order of 10,000 km^2. One feasible strategy is to select one region made up of several mesoscale basins as the primary region for intensive research and to select a small number of secondary basins representing a more diverse set of environments for additional characterization.

In order to characterize different parts of the basin in meaningful ways, sampling designs beyond the catchment approach are required. In particular, floodplain and flooded savanna environments cannot be isolated for rigorous input-output measurements. Sampling transects of soil solution and trace gas fluxes from uplands through lowlands and into surface waters can identify the sequence of substrate and oxidation/reduction conditions which control the partitioning and degradation pathways without construction of complete budgets. In a similar technique, processes can be tracked while sampling along a transect through different land-use areas at roughly the same topographic level. Distributed surveys of stream chemistry in diverse natural settings and land-use patterns will allow an extension of the models that would be developed in the more intensive study areas. In some cases, it may be possible to extend sampling of tracers back in time by looking for areas of steady sediment accumulation (106,107).

In addressing the broadest scale, that of the entire Amazon basin, it becomes possible to compare the responses of different environments across the basin. At this scale, as well as at the mesoscale discussed above, two types of tools become important. First, several organizations have made efforts to construct datasets which cover all or most of the Amazon basin, including the following: Datasets from the Brazilian RADAM campaign in the 1970's, consisting of SLAR images and concurrent studies of vegetative cover, soils etc, in the Brazilian Amazon; the land-system classifications of the Center for Tropical Agriculture in Cali, Colombia (108); records of the Brazilian Departamento Nacional de Águas e Energia Elétrica from their network of hydrological monitoring stations; water-quality measurements at tributary and mainstem points, especially the long-time series at Marchantaria, made by CAMREX (109).

The second set of tools consists of the many remote sensors available: Landsat TM and MSS products, now available for more than the past 20 years; radar products, including the results of several recent and on-going radar-based campaigns in the Amazon, which hold the promise of better defining the moisture status of the basin, extent of inundation, and forest structure (110); passive microwave data, which have been used to define the extent of inundation in the parts of the Amazon (111).

These datasets and remotely-sensed products can provide inputs to models. Currently most large-scale biogeochemical models operate solely in the vertical component, but in studying the low-lying areas and surface water of a basin, models must also address the horizontal transfers across the landscape. In addition, models must incorporate the anaerobic processes that occur in moist or saturated environments. Basin-scale modeling would be based on hydrologic routing modeling and the process-level understanding derived from the previous experiments in this section. At this scale, the dynamics of factors controlling output from smaller basins would be aggregated, and the subsequent output would be comparable to the whole-basin scale of the hydrology and energy experiments.

One way of testing such models is based on the division of the region into the basins of the major tributaries, since it is feasible to monitor chemical fluxes at the mouths of these basins. Time-series measurements of dissolved and particulate fractions can provide a continuous, integrated record of upstream processes. This record will vary systematically with changing interactions of flowing water with the landscape (109,112,113,114). Models of these large basins can be tested against these records and then used to predict the output hydrographs of water and chemical constituents (versus the measured time series) under different conditions of land use. ■

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