The Biogeochemistry of the Amazon Basin

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The Relevance of Biogeochemistry to Amazon Development and Conservation

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To read the press of recent years, one might imagine that the fate of the world rests in the hands of those who would develop the Amazon basin. Waves of incoming colonists are blamed for the bulk of the deforestation and development (Schomberg 1998), but Asian logging firms, multinational oil companies, and gold miners are also portrayed as destructive agents hacking down the forest, systematically undermining its biodiversity, and severely contaminating its myriad ecosystems (Althaus 1996, Ferreira 1996, James 1998). The effects of these varied threats are regularly broadcast in alarming tones. Rueters News Service warned in January 1998 that "Brazil's Amazon rain forest, the world's richest trove of biological diversity and source of much of the Earth's oxygen, continues to be ravaged" (Craig 1998). And, in April 1999, a writer for the Associated Press communicated the "fear" of unspecified scientists that "damage to the rain forest... could throw the Earth's climate out of balance" (Donn 1999).

Clearly, the fate of the Amazon and the implications of its fate to the overall Earth system are topics of enormous scientific and popular interest. While there is little disagreement that the complete destruction of Amazon forests would be catastrophic, what about partial deforestation of the region? How much, and which parts, of the Amazon can be converted to sustainable human land uses without compromising the ecological integrity of the conserved areas? How might this development impact regional climate, adjoining coastal systems, and overall global processes? Answers to these volatile questions remain elusive and seemingly endless strands of controversy swirl about them.

At the heart of the matter, yet largely beyond the public discussion, are biogeochemical cycles that support and regulate the functioning of the Amazonia's biological systems. Moreover, it is the incomplete understanding of these cycles that promotes uncertainty and feeds the controversy. The purpose of this book is to present a coherent assessment of our current understanding of the biogeochemical functioning of the Amazon basin. Although it is surely presumptuous to assume that this presentation will shed sufficient light on the uncertainties to eliminate the current controversies, we hope that it will provide a basis for lifting the discussion to a higher level.

Cycles of carbon, nitrogen, phosphorus, oxygen, and many other bioactive elements link the region's flora and fauna to associated cycles of water, soil, and seasonal energy fluxes. Research into the biogeochemistry of Amazonia's natural ecosystems has revealed an unprecedented level of sophistication of adaptive mechanisms within the flora and fauna for conserving and accessing nutrients. Replacement of native vegetation with poorly adapted crops and pasture grasses often leads to problems of nutrient availability and ultimately to crop failure and pasture degradation. Sustainable agrarian development in Amazonia is thus intimately related to fundamental biogeochemical processes and to our understanding of those processes.

Flora and fauna composing the expansive aquatic ecosystems exhibit a similar level of adaptive sophistication, which enables a rich diversity of organisms to flourish in spite of modest nutrient inputs from lowland terrestrial systems. The bounty of aquatic resources and water itself provides many essential services to the people of the Amazon. The region's natural fisheries provide a large proportion, and sometimes the majority, of animal protein consumed by inhabitants. Fish are also a valuable source of income to fishermen. River and lake water satisfies nearly all of the water supply needs of Amazon peoples, including drinking, cooking, bathing, and waste removal. While little water is used for irrigation, river channels and lakes are important avenues of transportation and shipping. Water bodies also provide abundant opportunities for recreation and are enjoyed in this way by most of the region's inhabitants.

With each of the above-mentioned uses of water, quality (or chemical purity) is crucial. This is especially true because water is generally not treated prior to human use in the Amazon. Threats to water quality include excess erosion and nutrient runoff from poorly managed fields and pastures, metal pollution from mining and other industrial activities, and organic pollution from the discharge of untreated human and animal wastes. The capacity of the river system to assimilate these threats varies as a function of discharge and biogeochemical processes operating to eliminate harmful conditions (McClain 2001).

On a global scale, and as Earth's largest conterminous area of wet tropical forest, the Amazon is viewed as a significant regulator of global greenhouse gases. Recent articles have highlighted the Amazon's role as a carbon dioxide sink (Prentice and Lloyd 1998), and modeling results suggest that Amazon vegetation may account for between 5% and 35% of the terrestrial sink for excess CO_2 in the atmosphere (Tian et al. 1998). Conversely, during El Niño years when the Amazon is drier than normal, these same modeling results suggest that Amazon vegetation may serve as a net source of CO_2 to the atmosphere. The Amazon is also a significant source of other greenhouse gases such as methane and nitrous oxide. When these gaseous emissions are combined with strong energy transfers linked to evaporation over the basin, the role of the Amazon in regional and global climate grows well beyond the areal coverage of the basin. By considering the quantitative impact that Amazon development may have on these emissions and energy transfers, one begins to understand the "fear" voiced in the opening paragraph.

Each year, the Amazon river discharges nearly 20% of the total volume of water delivered to the oceans by rivers. In fact, the annual discharge of the Amazon is greater than the combined annual discharge of Earth's next eight largest rivers! Accompanying this huge volume of water are correspondingly large loads of salts, metals, organic compounds, and sediments. These inputs to the Atlantic Ocean take on both regional and global significance by fueling coastal productivity and significantly impacting the global cycles of certain elements.

Biogeochemical Cycles in the Atmosphere - Global Linkages

Biogeochemical cycles in the Amazon basin are linked to global cycles through exchange with the atmosphere and river discharge into the Atlantic Ocean. Of these two, exchange with the atmosphere is by far the most interactive and variable on seasonal and inter annual time scales. Furthermore, it is through atmospheric exchanges that the Amazon interacts directly with the global climate system. In chapter 2, Jose Marengo and Carlos Nobre examine the nature of climatic variability over the Amazon and the influence of the basin within the global climate system. Over most of the Amazon temperatures are remarkably uniform and do not vary appreciably with season. The Andean Amazon is of course an important exception, as temperatures there vary over large ranges. Precipitation, however, varies significantly with space and time throughout the basin and stands as the most important climatic variable in explaining the nature, distribution, and magnitude of certain biogeochemical processes. Variability in rainfall is tied to large-scale circulation patterns of air masses in the region and the interactions of these air masses with ocean surface waters. The tight coupling of these processes is evidenced by the profound impacts that El Niño Southern Oscillation (ENSO) events have upon rainfall in the basin. Overall, the Amazon experiences reduced rainfall during ENSO events, although certain areas experience elevated rains. The impact of such anomalies on land and aquatic biogeochemical cycles is likely to be significant but has not been adequately assessed as yet.

The general reduction in rainfall across the Amazon during ENSO events raises the specter that global warming will produce similar reductions. This threat is amplified by the results of a growing number of large-scale modeling efforts, which consistently show a decrease in precipitation due to deforestation. The combined effects of these disturbances could significantly alter the cycling of water and associated elements in the Amazon.

In addition to climatic influences on land and aquatic biogeochemical cycles, there are also exchanges of bioactive elements between the Amazon surface and atmosphere. These exchanges take the form of gases and aerosols, which have direct impacts on regional and global climate. In chapter 3, Paulo Artaxo discusses the forms and dynamics of these exchanges. Each year, Amazon forests and savannas emit large quantities of aerosols and associated bioactive elements to the atmosphere. In general, higher concentrations of bioactive elements are found in the coarser fraction of aerosols, which are recycled within the region itself. The finer fraction, however, may be transported for thousands of kilometers and thus exit the Amazon region. Atmospheric transport out of the region, although still poorly quantified, probably represents a significant loss of nutrients from the basin. During the dry season, when slash burning is most practiced, concentrations of aerosols in the less than 10 µm fraction increase by an order of magnitude to values ranging from 400-500 $\mu g\ m^{-3}$. Under certain circumstances of enhanced convection, these aerosols may rise to altitudes approaching 10 kilometers, where transport velocities are greatly accelerated and their distribution may be global.

The biogeochemical roles of rainfall, aerosol, and gas emissions converge in the form of wet deposition, which is well documented as a significant source of nutrients and organic matter to Amazon surface systems (Andreae et al. 1990, Lesack and Melack 1996, Williams et al. 1997a). Important components of wet deposition are organic acids, which control rain pH values, and essential nutrients like phosphorus (P) and potassium (K).

Biogeochemical Cycles on Land - Coping with Nutrient Scarcity

According to an assessment by Ozório de Almeida and Campari (1995), the bulk of deforestation in the Brazilian Amazon is carried out by people moving within the basin, as opposed to newly arriving colonists.

The internal movement is prompted by a loss in soil fertility, which drives families to abandon their pastures and fields and to clear new land elsewhere. An essential element in reducing deforestation is thus improving management of cultivated land, thereby extending its use and reducing the rate of land abandonment. Widespread use of fertilizers and highly mechanized agriculture is impractical for most people in the Amazon. So, improved land management for nutrient conservation must make maximal use of natural mechanisms of nutrient recycling and conservation.

Management practices imported to the region regularly fail because they are adapted to conditions different than those present in the Amazon. New practices must be developed that are best suited to Amazon nutrient and soil/climate conditions. The luxurious growth which typifies Amazon forest is a clear indication that natural vegetation is well adapted to nutrient/soil/climate conditions of the region. Thus, important insights to sustainable land use are likely to be found by carefully examining the functioning of these systems.

Forests and savannas

In chapter 4, Elvira Cuevas examines the mechanisms through which terra firme (or nonflooded) forests of the Amazon satisfy their nutrient needs on the generally nutrient-poor soils that cover greater than 80% of the basin. On these soils, forest growth is limited mainly by P, calcium (Ca), and magnesium (Mg), as evidenced by significant correlations between forest productivity measures and abundances of these elements (Cuevas and Medina 1986, Cuevas and Medina 1988). Strong and persistent leaching processes have severely depleted many Amazon soils in Ca and Mg and have produced conditions under which mineral forms of P are bound to iron and aluminum oxides and generally unavailable to plants. Under these conditions, the key to sustained nutrient flows seems to lie in organic pools of these elements and the vegetation's adaptations to access these pools. Along a toposequence in the upper Negro basin of Venezuela, Tiessen et al. (1994 a, b) documented that greater than 70% of available P occurred at the surface and in the upper organic horizons of the soil column. Of this P, 50% occurred in particulate organic matter with a mean residence time of 4 years. The remaining mineral-associated P cycled over much longer time periods or was permanently sequestered in lateritic nodules.

Amazon forest plants access organic pools of P, Ca, and Mg through surface mats of fine roots and symbiotic interactions with mycorrhizae fungi. Root mats in Amazon forests on average account for 30% of the total fine root mass, and root mat thickness is inversely correlated with nutrient availability. Mycorrhizae fungi stimulate phosphatase production in the vicinity of fine roots and thus enhance the availability of PO_4 for uptake by fine roots. In fact, the combined action of surficial fine roots and mycorrhizae fungi has been shown to retain nearly 100% of added ^{32}P in uptake experiments in the upper Negro basin (Cuevas and Medina 1988). It is important to note here that this emphasis on recycling means that the productivity of Amazon forests is linked to the rate of nutrient remineralization rather than the standing stock of nutrients at anytime. Furthermore, these recycling mechanisms are a direct adaptation to the humid conditions of the Amazon, where extreme leaching potential necessitates the concentration of fine roots at the surface and abundant water makes this root allocation scheme functionally possible.

In the more arid savanna regions of the Amazon basin and Brazilian Cerrado, the problem of nutrient depleted soils is compounded by seasonal water shortages. As discussed by M. Haridasan in chapter 5, savanna vegetation is thus of greatly reduced biomass, with correspondingly reduced rates of nutrient cycling. Very little research has been conducted into the biogeochemical processes which link vegetation productivity to nutrient pools, but one especially important consideration is the role of fire in injecting periodic pulses of available nutrients into the system. Trees of the Cerrado are well adapted to the frequent fires and are seldom killed. Total vegetation cover responds quickly after fires and generally recovers with a few months of the fire event (Haridasan, this volume).

Pastures, plantations, and extractive reserves

The conversion of Amazon forest to other land uses sends a shock through the ecosystem which significantly impacts underlying biogeochemical cycles. Deforestation accompanied by slash removal and burning initially releases large quantities of carbon and nitrogen to the atmosphere and decreases the standing stocks of these elements. Mineral nutrients such as P, Ca, Mg, and K are concentrated in ashes and are returned to the soil column as a pulse accompanying infiltrating rainwater. These transformations are most dramatic and enduring in the conversion of forest to pasture, where grasses replace trees and cattle replace forest animals. The widespread creation of pastures in the Amazon has met with limited success because pasture productivity generally declines within three to five years of establishment, leading to expensive rehabilitation or, more likely, pasture abandonment. The key to extended pasture productivity lies in better management of nutrient cycles and therefore pasture fertility.

In chapter 6, Moacyr Dias-Filho, Eric Davidson, and Cláudio Reis de Carvalho discuss the role of biogeochemical cycles in regulating pasture productivity. The biogeochemistry of P is shown to be of particular importance, as this element is most limiting. Of the approximately 200 kg ha^{-1} of P measured in the soils of one pasture in the eastern Amazon, less than 1% is thought to be available to plants. Because only a very small pool of P is available to maintain pasture grasses, and fertilization is economically difficult, management techniques which are normally ignored become important. For example, the animals themselves become a key link in the cycle which replenishes available P. Instead of returning to the soil surface as litterfall, as would be the case in natural Amazon forests, P taken up by plants is returned to the soil surface mainly as animal feces. This, in turn, leads to problems of P distribution, as cattle tend to deposit feces in concentrated areas rather than uniformly across the pasture (Buschbacher 1987). Cattle also alter nutrient cycles by compressing the soil surface and promoting overland hydrological flows and greater losses of P.

Pasture creation impacts carbon (C) and nitrogen (N) cycles by reducing standing stocks and cycling rates of these elements. The main loss of C and N of course occurs in the aboveground biomass. In fact, C and N stocks may actually increase in pasture soils, but such increases are unpredictable and dependent on factors such as native soil fertility, fertilization, climate, fire frequency, and grazing intensity (Dias-Filho et al., this volume). Although standing stocks may rise or fall, research from the eastern and western Amazon shows that cycling rates consistently decrease. Net N mineralization and nitrification rates in pastures were found to range from less than 15% to 40% of rates measured in adjacent primary forest (unpublished data from Verchot and Davidson, presented in Dias-Filho et al., this volume). Similar patterns were observed for emissions of NO and N_2O gases. These sharply reduced rates of N cycling raise the question of whether N might become limiting under certain conditions in Amazon pastures or secondary forests.

As described by Florencia Montagnini in chapter 7, large-scale conversion of forest to silvicultural plantations has been carried out with generally disappointing results in the Amazon. Expansive stands of commercial species are highly susceptible to pests and disease, and in the Amazon they are dependent on additions of fertilizers to sustain multiple rotations. Thus it appears that such large-scale silviculture is unlikely to become a widespread use of Amazon land. Smaller scale mixed plantations, however, have a far greater potential as a sustainable land use and moreover as a tool in the rehabilitation of degraded landscapes. Such small-scale plantations place lesser demands on nutrient supply mechanisms and conserve a greater percentage of the system's natural nutrient conservation processes. Recognizing the special importance of organic nutrient pools in Amazon ecosystems, plantations can be used to produce mulch for effective nutrient application to crops or other managed lands. Depending on the nutrient content of different mulches and their biodegradability, specific needs can be satisfied. For example, quickly decomposing mulch may be added to short rotation crops to provide a pulse of nutrients to stimulate growth, or more slowly decomposing mulch may be applied to facilitate a more continuous source of nutrients. An especially valuable role for small plantations is the rehabilitation of degraded sites (Montagnini, this volume). Planting species with high nutrient use efficiencies will more quickly replenish organic matter levels in degraded soils.

The form of Amazon land use which least impacts natural biogeochemical cycles is extractive reserves. In chapter 8, Foster Brown, Karen Kainer, and Eufran do Amaral describe how a typical extractivist household "stores" more than 50,000 Mg of carbon in their managed forest. A large portion of this carbon would have otherwise been released to the atmosphere as CO_2 if the forest had been cut. Because the forest remains intact, so do other components of the natural biogeochemical cycles of C, N, P, Ca, Mg, and other bioactive elements. Although extractive reserves are suitable for only 25% of the Brazilian Amazon, they could serve an important role in reducing emissions of C and N to the atmosphere.

Secondary forest

As a result of the high rates of land abandonment in the Amazon, a great deal of land is undergoing forest regeneration. The rate of recovery of secondary forest is partially controlled by biogeochemical controls linked to soil fertility, and the forest itself plays a role in larger biogeochemical cycles by sequestering C and N within its increasing biomass, thus partially offsetting emissions from deforested areas. In chapter 9, Daniel Nepstad, Paulo Moutinho, Daniel Markewitz and Elizabeth Cheng calculate that carbon sequestration in second growth forests amounts to approximately 10% of that released through deforestation. These authors also raise the very intriguing issue of deep roots and their role in accessing nutrients for secondary forest growth.

The significant investment made in superficial roots by trees of Amazon forests is a clear indication of the importance of nutrient recycling from organic pools at the soil surface. However, research from the central and eastern Amazon has shown that trees in seasonally dry forests also have roots extending to at least 18 m depth (Nepstad et al. 1994). While the main function of these roots appears to be the uptake of deep soil water and groundwater, there is also potential for these roots to access deeper nutrient pools in the soil column. Nepstad et al. (this volume) elaborate on this issue by demonstrating that secondary forests growing in the eastern Amazon have P and K nutrient needs that cannot be satisfied by available stocks in the upper soil levels. They also show that secondary forests may re-establish deep root systems (6 m deep) within 16 years. They further show that abundant fine roots infected with mycorrhizal fungi characterize the deep roots of secondary forest. These circumstantial data suggest that secondary forests are mining nutrient reserves in deeper soils, but conclusive data are still unavailable.

Economic consequences of nutrient scarcity on land

Sustainable development in the Amazon hinges upon many factors which are ecological, physical, cultural, and economical. Among the most practical aspects of biogeochemical cycles in the Amazon are those that exhibit direct economical ties. In chapter 10, Carl Jordan discusses the interacting forces that bridge the gap between biogeochemical science and development economics. He recounts the dismal performance of such grand projects as the Jarí plantation and the reported failure of as much as 85% of the ranches in a section of the eastern Amazon. Although intensive agriculture, characterized by application of fertilizers and pesticides, has been shown to be profitable in select parts of the Amazon, in general the inhabitants of the region must look to alternative means of economic development. Jordan asserts that production systems in the Amazon must be designed in such a way to mimic the structure of the original forest and its natural nutrient conserving mechanisms.

Carbon storage

The consequences of deforestation, land management, and secondary growth extend beyond regional issues of conservation and sustainable land use to global issues of climate change. With CO_2 and CH_4 levels continuing to rise in the atmosphere, many global change scientists view the Amazon as a key variable in the global carbon budget. Will the Amazon's forests act as a sink for atmospheric CO_2, or will deforestation and burning of the region's forests only exacerbate the problem? Answers to these questions depend on the course of development (or conservation) in the region, but they also depend on exactly how much carbon the region's biota and soils can effectively hold. In chapter 11, Martial Bernoux, Paulo Graça, Carlos Cerri, Philip Fearnside, Brigitte Feigl, and Marisa Piccolo provide a detailed assessment of the quantity of carbon stored in soils and biota of the Brazilian Amazon basin. In total, the Brazilian Amazon is estimated to store more than 120 Pg (10^{15}g) of reduced carbon, of which 34% is held in soils and 66% is held in aboveground vegetation. Of the several natural and managed vegetation types in the Amazon, natural forest is the most important C repository, accounting for 97% of the aboveground C. These estimates are likely to improve as more data are collected and better techniques of extrapolation are developed. However, it is already clear that the Amazon is a major reservoir of reduced carbon on the globe.

Biogeochemical Cycles in Aquatic Systems - The Balance of Water Quality

Water is abundant in the Amazon, and nearly all living things in the basin are somehow dependent on this abundance. From the standpoint of development and conservation, the most crucial issue in water management is water quality. Clean water is fundamental to the maintenance of the Amazon's unique aquatic ecosystems and to the health of its people, who rely on surface water to satisfy their household water needs and to provide fish and other aquatic plants and organisms for their nutritional needs. Water quality is intricately linked to biogeochemical reactions such as the dissolution and decomposition of organic wastes, the transport and scavenging of heavy metals, and the regulation of proper nutrient levels. These processes are similarly linked to hydrological variability in the system, which determines transport conditions and dilution through mixing.

The continued development of the Amazon basin will increase demands placed on the region's surface water resources. In light of the limited economic resources of the nations composing the basin, it is likely that development will proceed without the implementation of adequate pollution control measures. For most activities, pollution "control" will be left to the natural assimilation capacity of the surface water system (McClain 2001). This is especially true in connection with the diffuse development activities in rural areas and small towns. Consequently, there is an acute need to better understand how the river system processes and transports organic matter, nutrients, and metals.

Streams

Streams are perhaps the most sensitive components of the surface water system to processes on land due to their small size and limited dilution capabilities. In chapter 12, Helmut Elsenbeer and I examine the role of streams in processing material and solute inputs from the Amazon landscape. Detailed studies of biogeochemical processes in Amazon streams have been limited to only a few sites, but results from these sites clearly indicate that inputs to streams from forests vary as a function of soils, geomorphology, and rainfall characteristics. In the nutrient depleted soils of the central Amazon, inputs of ions to the stream systems are reduced and a significant proportion of ions, including Ca, Mg, and K, may derive from vegetation sources via throughfall and overland flow of storm waters. Organic matter and inorganic nitrogen also appear to derive largely from riparian forests and wetlands in this region, thus the influence of upland forests is reduced (McClain and Elsenbeer this volume). The generally greater relief of the western Amazon Andean foothills forms narrower stream valleys with less pronounced riparian wetland zones and therefore greater connectivity between streams and upland forests.

The strong heterotrophic nature of Amazon streams makes them efficient at retaining both nutrients and organic matter input from adjoining lands. However, the capacity of these streams to assimilate contaminant levels of these same compounds is likely to be small. The greatest buffering capacity of Amazon stream systems likely lies in the riparian forest/wetland systems that adjoin them. Research by McClain et al. (1994) and Williams et al. (1997b) has demonstrated the ability of processes in the riparian zones of central Amazon watersheds to strip nitrate from upland groundwaters in forested and deforested settings. In the undisturbed setting of the Barro Branco stream, nitrate levels were reduced by 80% in comparison with levels in upland groundwater entering the riparian zone (McClain et al. 1994). Williams et al. (1997b) found that groundwater nitrate concentrations were elevated in groundwater following cutting and burning of the forest, but upon passing through the riparian zone levels decreased significantly. The same authors reported that intact riparian forest effectively buffered the stream from erosive inputs and their associated particulate nutrient and organic matter inputs.

Lakes and floodplains

More than 1 million square kilometers of the Amazon basin may be classified as floodplain, wetland, or lake. These environments range from narrow, sporadically flooded lowlands bordering streams to massive, regularly flooded plains bordering the basin's largest rivers. Nearly 9000 lakes, covering an average maximum area of 67,900 km^2, occur as integrated components of the massive floodplains bordering the mainstem Amazon and its major tributaries (Sippel et al. 1992). These varied aquatic habitats play a pivotal role in many ecological, as well as biogeochemical, processes in the region. From a practical standpoint, floodplains and their associated lakes provide essential breeding and feeding areas for many of the Amazon's most economically important fish species (Goulding 1980). Along whitewater rivers rich with Andean sediment, floodplains also provide fertile soils for crops and pasture. Finally, these environments emit quantities of methane that are significant in the global atmospheric methane budget and relevant to studies of climate change (Bartlett and Harriss 1993).

In chapter 13, Maria Teresa Piedade, Martin Worbes, and Wolfgang Junk examine the strong links between ecological aspects of the higher plants and elemental fluxes on Amazon floodplains. Distribution, species composition, biomass, and primary productivity constitute fundamental ecological parameters that exert marked control over elemental fluxes. Piedade et al. show that these parameters are in turn linked to interacting geomorphological and hydrological factors. The most influential combined effect of geomorphology and hydrology is period of inundation, which corresponds to the number of days per year that a given point is submerged by the oscillating flood waters. Species of the flooded forest are organized into zones which relate directly to period of inundation. Species distributions throughout these zones vary as a function of both the degree of stress imposed and the adaptive strategies employed by the trees. Within the herbaceous community, distribution patterns also vary according to the balance between floodpulse-induced stresses and adaptive strategies, but additional factors linked to physical stability are also important. A final control on species distributions is the biogeochemical nature of the river water and sediments. Distinct types of floodplain forest develop adjacent to whitewater rivers (várzea) and blackwater rivers (igapó).

Piedade et al. show that geoecological variables impact both the magnitude and timing of elemental fluxes in floodplains. Leaves of flooded forest in várzea are significantly enriched in nutrients in comparison to leaves of flooded forest in igapó, and when combined with productivity data these foliar nutrient levels indicate more efficient nutrient use in igapó forest. By taking a more in-depth look at N pools and dynamics of the várzea forest, Piedade et al. conclude that approximately 200 kg ha^{-1} of N (and associated nutrients) are input to the floodplain in the form of fresh leaf matter annually. The annual pulse of nutrient input is even more dramatic in floodplain herbaceous communities, which turnover completely each year. A stand of the grass *Echinochloa polystachya* was found to take up 377 kg ha^{-1} of N from river water and to return it to the soil surface as fresh organic litter. Corresponding inputs of P and K were 51 and 1136 kg ha^{-1}, respectively. Transformations such as these in nutrient forms are essential in maintaining the overall fertility of the environment and also feeding the food chains which support commercially important fish species.

In chapter 14, John Melack and Bruce Forsberg provide a quantitative assessment of the role of floodplain lakes in regional cycles of C, N, and P. Floodplain lakes were found to be important centers of organic carbon production and delivery to the river system. The combined primary production of macrophytes, forests, periphyton, and plankton associated with floodplain lakes is estimated at 117 Tg C yr^{-1}, of which only 24% is remineralized in the lakes. As a result, an estimated 90 Tg C yr^{-1} are delivered to the river system by continual and seasonal exchanges. This input alone amounts to more than twice the annual export of organic C in the river system. Given that the river also receives organic C inputs from vast upland forests and other parts of the floodplain, these new data suggest that consumption of organic C is likely to be far higher in the river's mainstem than had been previously thought (see next section). Cycling of N and P in these lakes is closely correlated with that of organic C. According to Melack and Forsberg, productivity in floodplain lakes may be limited by either N or P in conjunction with spatial and temporal differences in the supplies of these nutrients across the spectrum of lakes.

Melack and Forsberg discuss an array of anthropogenic impacts on Amazon floodplain lakes, including mining, hydroelectric dams, mercury pollution, and deforestation of adjoining uplands. Each of these activities upsets normal cycles of important elements, either by poisoning organisms which carryout the cycling (mining wastes and mercury pollution), altering the cycle of flooding to which organisms are adapted (dams), or otherwise changing the natural rates and forms of element inputs (dams, mining, and deforestation). Specific impacts of these activities are still mostly unstudied in the Amazon, but in light of the crucial role floodplain lakes play in larger elemental cycles and associated ecosystem products (for example, fisheries), negative impacts there are likely to propagate to much wider areas.

The mainstem river and its estuary

The flow of water, solutes, and particulate matter in the mainstem Amazon river is the product of integrated hydrological, biological, physical, and biogeochemical processes across the entire basin. Of the many natural features of the Amazon, none more completely integrates these processes, because there is no corner of the basin that does not contribute some proportion of its water and associated load to the river system. The condition of the river may thus be viewed as a kind of proxy for the condition of the larger basin. As with aquatic resources throughout the Amazon, water quantity is not a problem, with the exception of occasional extreme flooding events. The main issue is water quality and the maintenance of water quality within ranges appropriate to support natural aquatic ecosystems and the water needs of the human population.

Water quality in the mainstem Amazon remains excellent, with the exception of isolated sites of relatively small-scale contamination near the river's big cities. Thus biogeochemical investigations of the river enjoy the luxury of focusing mainly on natural, or background, compositional patterns and dynamics. In chapter 15, Alan Devol and John Hedges examine the relative role of upstream sources and in-channel processing in determining the dynamics of C, N, P, and oxygen (O) in the mainstem river. The major proportion of organic matter transported in the mainstem is refractory material of upstream origin, which appears to pass through the mainstem rather conservatively. Heterotrophic metabolism is fueled by a smaller, more labile pool of organic matter derived from local sources such as the floodplain (see Melack and Forsberg, above). Because the Amazon mainstem is almost entirely heterotrophic, the foodweb of the river's myriad aquatic organisms is based on the input of energy and nutrients from this more labile organic matter pool. Nearly all fine particulate forms of C, N, and P in the mainstem derive from Andean environments many thousands of kilometers upstream. This is a striking example of the interconnectivity and interdependency of processes across the Amazon.

In an especially interesting application of biogeochemical investigative techniques, Devol and Hedges use rather sophisticated molecular and isotopic biomarkers to illuminate the finer details of organic matter dynamics in the mainstem. Sources of the main organic matter pools (dissolved, fine particulate, and coarse particulate) are identified using concordant data on elemental ratios, carbon stable isotope ratios, and relative abundances of specific compounds derived from lignin molecules. These data suggest that terrestrial vegetation is the predominant source of organic matter (OM) in the river, as opposed to plankton or floodplain grasses. Furthermore, subcomponents of the lignin molecular fraction point specifically to leaves as the source instead of the woody portions of trees. The course and degree of degradation within the OM fractions is shown to be quite distinct based on abundances of carbohydrates, amino acids, and lignin fractions. Dissolved OM is the most highly degraded fraction, while coarse particulate OM retains molecular signatures that are closest to fresh leaf material and fine particulate OM lies in between. When analyzed more closely, the consistent patterns in elemental and molecular variability between the fractions suggest that differential partitioning (or sorption) may account for final separation of refractory molecules into the fine particulate or dissolved phases. The transport dynamics implied by the foregoing data are confirmed by abundances of bomb carbon-14 in the different fractions.

Devol and Hedges synthesize the above results into an elegant conceptual model explaining the processing of organic matter carried by the Amazon mainstem. The model, which they refer to as "Regional Chromatography", follows the processing from production of leaf litter in the basin's forests until the arrival of the final refractory OM in the mainstem river. Within the model, coarse particulate OM is transported to the river system via quick overland hydrological flowpaths or direct litterfall, whereupon it undergoes rapid decomposition but still retains an appreciable proportion of its original biogeochemical signature upon reaching the mainstem. Conversely, fine particulate OM and dissolved OM are assumed to emanate from the soils after partitioning into their respective fractions, where movement to the river system occurs either as soil erosion (fine particulate OM) or subsurface runoff (dissolved OM). Although field investigations undertaken in upland portions of the basin to test the predictions of the Regional Chromatography model have not always yielded supporting data (McClain et al. 1997), the model continues to provide an internally consistent and conceptually appealing explanation for mainstem OM compositional patterns.

An additional set of elements which play important roles in reactions ranging from biogeochemical to purely geochemical are trace metals. In chapter 16, Patrick Seyler and Geraldo Boaventura present a comprehensive survey of trace metal forms and fluxes in the mainstem Amazon and its major tributaries. Trace metal abundances between the mainstem and its tributaries vary as a function of the source rocks occurring in the basins and in function with the reactivity of the metals. Concentrations of most metals in the Amazon are comparable to those in other major rivers of the world, and the Andes stand out as the dominant source area for most metals transported by the river. In the Amazon mainstem, trace metals are transported primarily in particulate form. Transport in the dissolved phase predominated only in the Negro River, where many metals were complexed with dissolved organic matter. Seyler and Boaventura present new data illustrating the temporal variability of trace metal fluxes in the main river system. They identified four discrete patterns of variability which reflect the source, process of mobilization, and in-channel reactivity of the metals measured.

Currently, trace metal pollution is not a problem in the Amazon River, with the exception perhaps of localized small-scale occurrences. However, the basin includes several sites of elevated metal releases linked to gold and manganese ore mining and industrial discharges from the large cities. Seyler and Boaventura discuss the likelihood of contamination from these sources. Moreover, they come to the provocative conclusion that elevated fluxes of manganese, copper, vanadium, arsenic, and nickel may already be detectable at the river's mouth due to anthropogenic activities in the basin. Possible metal contamination should be taken seriously in the Amazon, as even small amounts of the more toxic metals may lead to widespread adverse effects in the river's aquatic systems.

Whereas the Amazon River is the recipient of energy and nutrients provided by its upland basin and flood plain, it is an important provider of these things to the estuarine and coastal zone of the western Atlantic. In chapter 17, David DeMaster and Robert Aller examine the interactive physical and biogeochemical processes which regulate biological productivity on the Amazon shelf. In budgets calculated from recent data, they demonstrate that the river is the most important source of silica (Si) to the shelf area and therefore strongly controls production within the diatom community. Further-more, the bulk of this Si is not retained on the Amazon shelf but is instead transported offshore where it contributes to the nutrient needs of open-water plankton. The river is also an important source of P and N, but oceanic sources, and especially internal recycling, account for the largest inputs of these elements. Approximately 60% of riverine particulate organic C is remineralized on the shelf, mostly on the seafloor. This is a small fraction of heterotrophic activity, however, as more labile marine particulate organic C is greatly preferred by heterotrophic organisms. By analyzing the relationship between C and O budgets, DeMaster and Aller conclude that biological production is approximately balanced by consumption, such that the shelf area exhibits no obvious autotrophic or heterotrophic character.

The Challenge for Today and the Future

As the preceding paragraphs highlight, and as the following chapters will detail, biogeochemical cycles are at the heart of many of the key issues facing the Amazon basin. Both sustainable development and preservation of the region's unique ecosystems depend on our understanding of fundamental processes such as the balance of nutrients in land and aquatic ecosystems, the assimilation capacity of contaminants in these same ecosystems, and ultimately the tolerance of Amazon ecosystems to specific development pressures. The basin's singular importance in the larger Earth system means that the consequences of poor decisions in the Amazon will be felt in adjoining regions and perhaps even on the global scale.

Amazon biogeochemists face the challenge of advancing understanding at a rate greater than the advancing development. In other words, if sound scientific understanding is to guide sustainable develop in the Amazon, then research must move ahead of development. This is a formidable challenge due to the large size of the basin and the relatively small research budget devoted to Amazon research by countries composing the basin and the international scientific funding agencies. The challenge is made more difficult by the unique environmental circumstances found in the Amazon, and thus the limitations against applying models borrowed from more intensively studied systems outside the tropics. Many of the most notorious failures to date in the development of the Amazon have come from applying models of land and water management borrowed from temperate zones. Whether these models assume an unrealistic level of soil fertility, unachievable financial resources, or other conditions taken for granted in temperate zones, they are predisposed to failure.

Most biogeochemists working in the Amazon today understand that the key to sustainable development is to understand the integration of physical and biogeochemical factors responsible for the luxurious natural ecosystems of the basin and then to emulate or attempt to preserve these factors in development programs. There are currently several ambitious research programs that aim to do just that, and the leaders of many of these are the authors of the following chapters. I invite you the reader to delve into the volume of good research presented in this book and to make use of it in the manner that best suits your own professional position and that best enables you to join in our efforts to guide Amazon conservation and development into the future along a sustainable path.

Literature Cited

Althaus, D. 1996. "Amazon's empty legacy/Big oil responds to environment/Toll on rain forest, culture still unacceptable to critics." Houston Chronicle (TX), December 15, p. 27.

Andreae, M. O., R. W. Talbot, H. Berresheim, and K. M. Beecher. 1990. "Precipitation chemistry in Central Amazonia." Journal of Geophysical Research 95(D10): 16987-16999.

Bartlett, K. B., and R. C. Harriss. 1993. Review and assessment of methane emissions from wetlands. Chemosphere 26: 261-320.

Burns, M. K. 1998. "Biological diversity being eroded in Amazon: Even in an Ecuadorean national park, where rain forest species are supposed to be protected, colonization and poaching threaten the delicate ecosystem." The Sun (Baltimore, MD), April 23, p. 2A.

Buschbacher, R. 1987. "Cattle productivity and nutrient fluxes on an Amazon pasture." Biotropica 19: 200-207.

Craig, J. 1998. Ravaging of Brazil's Amazon continues - survey, Reuters, January 26.

Cuevas, E., E. and Medina. 1988. "Nutrient dynamics within Amazonian forests. II. Fine root growth, nutrient availability and leaf litter decomposition." Oecologia 76: 222-235.

Donn, J. 1999. Report: Amazon Rain Forest Fading, The Associated Press News Service, April 8, 1999.

Ferreira, L. 1996. "Asian logging companies turning to Amazon rain forest," Kyodo News International, Inc., June 4.

Gómez, R. 1994. "Contaminación Ambiental en la Amazonia Peruana." Informe Técnico de Avance of the Instituto de Investigaciones de la Amazonia, Peruana, Iquitos.

Goulding, M. 1980. The Fishes and the Forest. University of California Press, Los Angeles.

James, I. 1998. The Endangered People of Peru, St. Petersburg Times (FL), July 5, 1998 p. 1D .

Lesack, L. F. W., and J. M. Melack. 1996. "Mass balance of major solutes in a rainforest catchment in the Central Amazon: Implications for nutrient budgets in tropical rainforests." Biogeochemistry 32: 115-142.

McClain, M.E. 2001. "Ecohydrology as a tool in the sustainable development of large tropical rivers". In: Ecohydrology From Concepts to Application. Zalewski, M. (Cambridge University Press, New York).

McClain, M. E., J. E. Richey, J. A. Brandes, and T. P. Pimentel. 1997. "Dissolved organic matter and terrestrial-lotic linkages in the central Amazon basin of Brazil."Global Biogeochemical Cycles 11: 295-311.

McClain, M. E., J. E. Richey, and T. P. Pimentel. 1994. "Groundwater nitrogen dynamics at the terrestrial-lotic interface of a small catchment in the Central Amazon basin." Biogeochemistry 27: 113-127.

Nepstad, D. C., C. R. de Carvalho, E. A. Davidson, P. Jipp, P. Lefebvre, G. H. Negreiros, E. D. da Silva, T. Stone, S. Trumbore, and S. Vieira. 1994. "The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures." Nature 372: 666-669.

Ozório de Almeida, A. L., and J. S. Campari. 1995. Sustainable Settlement in the Brazilian Amazon. Oxford University Press, New York. p. 189.

Prentice, I. C., and J. Lloyd. 1998. "C-quest in the Amazon basin." Nature 396: 619-620.

Schomberg, W. 1998. Brazil says farmers are destroying the Amazon, Reuters, March 3.

Sippel, S. J., S. K. Hamilton, and J. M. Melack. 1992. "Inundation area and morphometry of lakes on the Amazon River floodplain, Brazil." Archiv für Hydrobiologie 123: 385-400.

Tian, H., J. M. Melillo, D. W Kicklighter, A. D McGuire, J. V. K. Helfrich, B. Moore, and C. J. Vörösmarty. 1998. "Effect of interannual climate variability on carbon storage in Amazonian ecosystems." Nature 396: 664-667.

Tiessen, H., E. Cuevas, and P. Chacón. 1994a. "The role of soil organic matter in sustaining soil fertility." Nature 371: 783-785.

Tiessen, H., P. Chacón, and E. Cuevas. 1994b. "Phosphorus and nitrogen status in soils along a toposequence of dystrophic rainforests on the upper Rio Negro." Oecologia 99: 145-150.

Williams, M. R., T. R. Fisher, and J. M. Melack. 1997a. "Chemical composition and deposition of rain in the central Amazon, Brazil," Atmospheric Environment 31, No. 2: 207-217.

Williams, M. R., T. R. Fisher, and J. M. Melack. 1997b. "Solute dynamics in soil water and groundwater in a central Amazon catchment undergoing deforestation." Biogeochemistry 38: 303-335.