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Globally significant changes in biological processes of the Amazon Basin: results of the Large-scale Biosphere–Atmosphere Experiment

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Abstract

The Amazon River, its huge basin, and the changes in biological processes that are rapidly occurring in this region are unquestionably of global significance. Hence, *Global Change Biology* is delighted to host a special thematic issue devoted to the Large-scale Biosphere–Atmosphere Experiment in Amazônia (LBA), which is a multinational, interdisciplinary research program led by Brazil. The goal of LBA is no less modest than its subject: to understand how Amazônia functions as a regional entity in the Earth system and how these functions are changing as a result of ongoing changes in land use. This compilation of 26 papers resulting from LBA-related research covers a broad range of topics: forest stocks of carbon (C) and nitrogen (N); fluxes of greenhouse gases and volatile organic compounds from vegetation, soils and wetlands; mapping and modeling land-use change, fire risk, and soil properties; measuring changes caused by logging, pasturing and cultivating; and new research approaches in meteorology to estimate nocturnal fluxes of C from forests and pastures. Some important new synthesis can be derived from these and other studies. The aboveground biomass of intact Amazonian forests appears to be a sink for atmospheric carbon dioxide (CO_2), while the wetlands and soils are a net source of atmospheric methane (CH_4) and nitrous oxide (N_2O), respectively. Land-use change has, so far, had only a minor effect on basin-wide emissions of CH_4 and N_2O, but the net effect of deforestation and reforestation appears to be a significant net release of CO_2 to the atmosphere. The sum of the 100-year global warming potentials (GWP) of these annual sources and sinks of CH_4, N_2O, and CO_2 indicate that the Amazonian forest–river system currently may be nearly balanced in terms of the net GWP of these biogenic atmospheric gases. Of course, large uncertainties remain for these estimates, but the papers published here demonstrate tremendous progress, and also large remaining hurdles, in narrowing these uncertainties in our understanding of how Amazônia functions as a regional entity in the Earth system.

Keywords: Amazon River, Brazil, climate change, global warming potential, land-use change, sustainable development, LBA

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Introduction

The Amazon River and the basin that it drains are truly epic in size and importance. The Amazon River discharges about 15–20% of the world's fresh water to the ocean, which is about five times greater than the Congo River and about 10 times greater than the Mississippi River. The forested area of the Amazon Basin is about four times larger than either of the world's next largest regions of tropical broadleaf forests remaining in the Congo and in Indonesia. Such a large area is obviously of great importance as a habitat for innumerable species of plants and animals. Perhaps somewhat less obvious is the importance of this vast forest–river system on global climate and as a source and sink of atmospheric carbon dioxide (CO_2) (Houghton *et al.*, 2000; Richey *et al.*, 2002) and atmospheric trace

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gases such as nitrous oxide (N_2O), methane (CH_4), and volatile organic carbon (C) compounds (Keller *et al*., 1997).

The Amazon Basin is changing rapidly. It is home to some 24 million people in Brazil, Bolivia, Peru, Ecuador, Columbia, and Venezuela. Agriculture, logging, and urbanization are expanding, and the forested area is shrinking. Annual rates of deforestation in the Brazilian Amazon ranged from 11 000 to 29 000 km^2 in the 1990s, which, on average, is about 0.5% per year (Houghton *et al*., 2000; GOB, 2002). A great challenge of our time is to meet the needs of the growing human population of the region while maintaining the critical ecosystem services provided by the forest and the river to local, regional, and global communities. Humans have been part of the Amazon system for many thousands of years, but their impact as agents of change in biogeochemical processes is accelerating at an unprecedented pace.

The Large-scale Biosphere–Atmosphere Experiment in Amazônia (LBA) is a multinational, interdisciplinary research program led by Brazil through its Ministry of Science and Technology. Its goal is to understand how Amazônia functions as a regional entity in the Earth system and how these functions are changing as a result of ongoing changes in land use. In addition to studying the biogeochemical and biophysical functioning of Amazônia, LBA seeks to contribute a scientific basis for addressing the sustainability of development in the region. The key question guiding the ecological studies within LBA has been defined as follows:

> ''How do tropical forest conversion, regrowth, and selective logging influence carbon storage, nutrient dynamics, trace gas fluxes and the prospect for sustainable land-use in the Amazon region?'' (Cerri *et al*., 1995).

The ambitiousness of the goal, the breadth of the question, and the immensity of the area call for the big science effort that is LBA. However, if this effort is to be more than the sum of its parts that are represented by each research team's publications, syntheses of how those papers fit together are needed. Special LBA thematic issues of other journals have emphasized LBA research related to atmospheric chemistry and physical climate (Avissar *et al*., 2002; Gash *et al*., in press) and applications of remote sensing (Roberts *et al*., 2003). An emphasis on ecological integration is the focus of other studies (Keller *et al*., in press) and those presented in this special LBA thematic issue of *Global Change Biology.*

Although this thematic issue was open to all new biological research associated with LBA, thus resulting in a wide array of topics, threads of synthesis can be traced through this array. Such synthesis is the objective of this introductory paper, which is divided into three sections. First, we summarize nine papers that address how C and nitrogen (N) cycle in the forest–river system when human influences are mostly absent. Second, a group of four papers describes the teleconnections among global and regional climate and temporal patterns of tree growth, primary productivity, fire susceptibility, and soil trace gas emissions. Anthropogenic influences are introduced in the third section, which reviews 12 papers covering mapping and modeling land-use change and changes in soil properties, selective logging, and C cycling in cattle pastures and rice fields. The final section on Amazônia as a regional entity begins with a brief review of a basin-wide modeling exercise to calculate net C emissions resulting from deforestation and reforestation. We then compare the relative magnitudes of greenhouse gas emissions and uptake rates from the mostly intact mature forest–river system and from the anthropogenically altered landscape in terms of global warming potential CO_2-equivalents.

C and N cycling in the Amazonian forest–river system

About 17% of the Amazon Basin is subject to flooding by the Amazon River and its tributaries (Melack *et al*., this issue). While aerobic respiration by vegetation and soil microbes accounts for most of the C respired by the Amazonian *terra firme* forest, anaerobic respiration, such as the methanogenesis that occurs in flooded soils and wetlands, is also a major biogenic product of the forest–river system. It is not surprising that warm, wet conditions of the floodplain promote significant CH_4 production, but quantifying the flux of this important greenhouse gas to the atmosphere is complicated by the dynamic and diverse wetland habitats along the many thousands of kilometers of stream and river corridors. Melack *et al*. (this issue) provide an error analysis of uncertainties both in estimates of average CH_4 emissions from these wetlands and in the areal extent of these wetlands in wet and dry seasons. Emissions from Amazonian wetlands alone appear to contribute about 4% of the global annual emissions of CH_4 from all natural and anthropogenic sources. As shown later in this paper, the global warming potential of the annual emissions of CH_4 from Amazonian wetlands is equivalent to about 30–40% of the estimated annual accumulation of C in woody biomass of mature Amazonian forests.

It might seem that it would be easier to estimate stocks and fluxes of C in forests rather than from wetlands, but the diversity of Amazonian forests and soils is also under-appreciated by many. In a pair of companion papers, Baker *et al*. (this issue) and Malhi *et al*. (this issue) analyze spatial variation across the basin, from the Andes to the Atlantic, of wood density, aboveground biomass, and tree growth rates. They found that the forests in the eastern and central Amazon Basin tend to have more dense wood, with greater standing biomass, and with longer mean residence time than in the western part of the basin. As one approaches the Andes, the forests become more dynamic, both growing faster (up to three times higher rates of aboveground wood production) and turning over faster (greater mortality). Soil analyses are underway in this regional gradient study, but the preliminary evidence presented here by Malhi *et al*. (this issue) suggests that the higher fertility of the soils near the Andes may explain the higher wood production rates there. After accounting for mortality, the estimated mean net increase in aboveground biomass of trees $>10\,\mathrm{cm}$ diameter during the last few decades in old-growth Amazonian forests is $0.6\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ (± 0.2; 95% confidence interval; Baker *et al*., 2004). Based on these data and assumptions about added increments for increases in C stocks of roots, small trees, and lianas, Mahli & Phillips (2004) have offered a basin-wide extrapolation of a $0.6\,\mathrm{Pg\,C\,yr^{-1}}$ CC sink in mature Amazonian forests. This estimate of a forest biomass sink for C does not include soil C stocks (Telles *et al*., 2003) or changes in coarse woody debris (Saleska *et al*., 2003), which are discussed further in the final section of this paper.

While soil fertility may vary at the basin scale, it also varies at more local scales, such as in the hill and valley topography studied near Manaus by Luizão *et al*. (this issue). These authors demonstrate a more conservative N cycle in the forest stands of the seasonally wet valley positions on Spodosols, compared with the well-drained plateau positions on Oxisols. By inference, lower rates of net primary productivity would be expected in the valleys. Working at the same plateau site, Sotta *et al*. (this issue) show how soil respiration varies seasonally and with individual rainfall events. Hence, temporal variation of climatic drivers plays an important role in addition to spatial patterns of soil fertility for determining fluxes of C through the forest ecosystem.

In addition to annual and seasonal variation, diel variation can be important, especially for some measurement techniques such as eddy covariance for measuring net ecosystem exchange of C. Very stable conditions within the forest canopy at night have been a major problem for interpreting these measurements in Amazonian forests (Goulden *et al*., in press; Saleska *et al*., 2003). Biases in night-time measurements can significantly inflate annual estimates of C sequestration by the ecosystem. Martens *et al*. (this issue) provide an independent check on nocturnal eddy covariance estimates by measuring profiles of radon gas, which permit calculation of C fluxes based on rates of accumulation of both radon and CO_2 during stable nocturnal conditions within the forest canopy. They demonstrate that good agreement between eddy covariance and radon-based estimates of carbon fluxes can be obtained when the eddy covariance estimates are corrected for biases caused by stable atmospheric conditions. Although such corrections may be site-specific and must be carried out with care, this new result should allow LBA researchers to harmonize their analytical approaches across eddy covariance sites. Methodological agreement among tower studies is needed in order to permit synthesis of eddy covariance measurements of carbon sequestration with biometric measurements such as those reported here by Malhi *et al*. (this issue).

So far, this discussion of spatial and temporal variation across the Amazon Basin has mostly ignored the tremendous diversity of species. Processes that are species-dependent could vary significantly among the various eco-regions and climatic patterns within the Amazon Basin. Do species matter with regard to biogeochemistry? Yes, according to a pair of companion papers that estimate biogenic volatile organic compounds (VOCs), such as isoprene and α-pinene emissions. Greenberg *et al*. (this issue) employed a top-down tethered balloon approach, while Harley *et al*. (this issue) adopted a bottom-up leaf measurement approach. Similar to the three-fold variation that Malhi *et al*. (this issue) reported for woody biomass production across the basin, these authors found a three-fold variation in emission rates of VOCs across study regions, and they attribute this variation to diverse species composition. In a separate study, Kuhn *et al*. (this issue) found up to a two-fold difference in isoprene emissions between wet and dry seasons in Rondônia.

Canopy emissions of VOCs amount to only a few percent of gross primary productivity (Guenther, 2002; Kesselmeier *et al*., 2002), but their effects on atmospheric chemical processes and physical climate processes far exceed their modest contribution to the C cycle. Biogenic hydrocarbons are critically important in the regulation of ozone, hydroxyl radical, and other important trace gases and radicals in tropical atmospheric chemistry. Terpenes also make aerosol particles that affect the radiation budget and that also act as cloud condensation nuclei in Amazônia. Hence, part of the precipitation formation mechanism could be controlled by the vegetation itself through terpene emission (Artaxo *et al*., 2001). Hence, links between the biosphere and the atmosphere may be extremely complex, with climate affecting VOC emissions and *vice versa*. Moreover, the new results published in this issue beg the question of how species composition and their strategies to produce VOCs in response to physiological stresses might be related to variation in climate, soil fertility, and C allocation.

Teleconnections between global climate and the forest–river system

It is well known that the eastern Amazon Basin experienced reduced rainfall during the 1982–1983 and 1997–1998 El Niño-Southern Oscillation (ENSO) events (Nepstad *et al*., 1999; Marengo & Nobre, 2001). Schoengart *et al*. (this issue) now extend the documentation of this effect back 200 years by using growth rings of trees growing in the seasonally inundated floodplains along the Amazon River. This long record enables them to demonstrate that the ENSO effect appears to have grown in severity. Potter *et al*. (this issue) also explore the relationship between ENSO, the Arctic Oscillation (AO) index, rainfall, and the fraction of absorbed photosynthetically active radiation (FPAR) observed by remote sensing. Their biogeochemical model uses variation in FPAR, among other factors, to infer rates of net primary productivity and net ecosystem productivity. The correlation between FPAR in Amazonian forests and the AO index is a novel finding that further demonstrates the connectivity of the Earth climate system and the importance of the Amazonian forest for global climate.

What are the broader implications of drought that may result from a combination of factors, including ENSO, less recirculation of water between the deforested biosphere and the atmosphere (Shukla *et al*., 1990; Nobre *et al*., 1991; Costa & Foley, 2000; Werth & Avissar, 2002) or from rainfall inhibition by smoke (Rosenfeld, 1999; Andreae *et al*., 2003)? Nepstad *et al*. (this issue) use a water balance model, precipitation records, and a GIS database on soil water holding properties to estimate the probability of flammability across the basin. While flames in a rainforest may seem counterintuitive, ENSO events can be sufficiently strong to increase the risk of fire. Nepstad *et al*. (this issue) show that about a third of the Amazonian forest probably experienced sufficient drought during the 2001 ENSO to cause a reduction in leaf area and an increase in flammability. They further speculate that rates of C sequestration in woody biomass of *terra firme* forests of the Amazon Basin could be reduced on the order of $0.2\,\mathrm{Pg\,C\,yr^{-1}}$ during ENSO events.

Drought also affects other important processes. In an experimentally induced drought, Davidson *et al*. (this issue) demonstrated that N_2O and CH_4 emissions from forest soils were reduced during drought. Of course, drought would also affect the area of wetlands, which could reduce CH_4 emissions (Melack *et al*., this issue) and increase the growth of varzea forest trees (Schoengart *et al*., this issue). Hence, the net effect of ENSO events on sources and sinks of greenhouse gases is complex and cannot yet be estimated, but these papers are establishing the foundation of understanding needed to attempt such a synthesis.

Despite such complexities, it is becoming clear that the Amazonian ecosystem is sensitive to global climate forcing agents. Fire risk is among those sensitivities to climate, but fire is also affected by management. Logging also thins the canopy and permits sunshine to dry the forest floor, while pasture management, charcoal production, and expansion of roads increase ignition sources (Alencar *et al*., in press; Fig. 1). Previous work has shown that, after an Amazonian forest stand has been burnt once, the reduced canopy cover and increased penetration of solar radiation to the forest floor increase the probability that fire will be able to spread through the stand again (Cochrane *et al*., 1999). The interactions of climate, management, and fire susceptibility produce several mechanisms of positive feedback that may lead to further forest degradation, fire risk, and negative economic and human health consequences (Fig. 1; Nepstad *et al*., 2001). Hence, processes such as fire in the Amazonian rainforest must be studied in the context of the anthropogenic changes occurring within it, which is the topic of the next section of this issue.

Changes in land use and land cover

Much of the focus of scientific investigations of land-use change in the Amazon Basin has been devoted to documenting the direction and rate of change and the biogeochemical consequences of those changes. This section of the issue begins with a new map of land cover of South America based on analysis by Eva *et al*. (this issue) of satellite imagery from 1995 to 2000. The expansion of agriculture into the Amazon Basin is apparent, but more importantly, this type of digital map can be used as an input to models of climate, biogeochemical processes, and socioeconomic activities.

While many of the papers in this issue address the biogeochemical consequences of deforestation, only Soares-Filho *et al*. (this issue) attempt to address the underlying factors that contribute to the causes of deforestation. These authors couple a scenario-generating model to a landscape dynamics simulator to explore

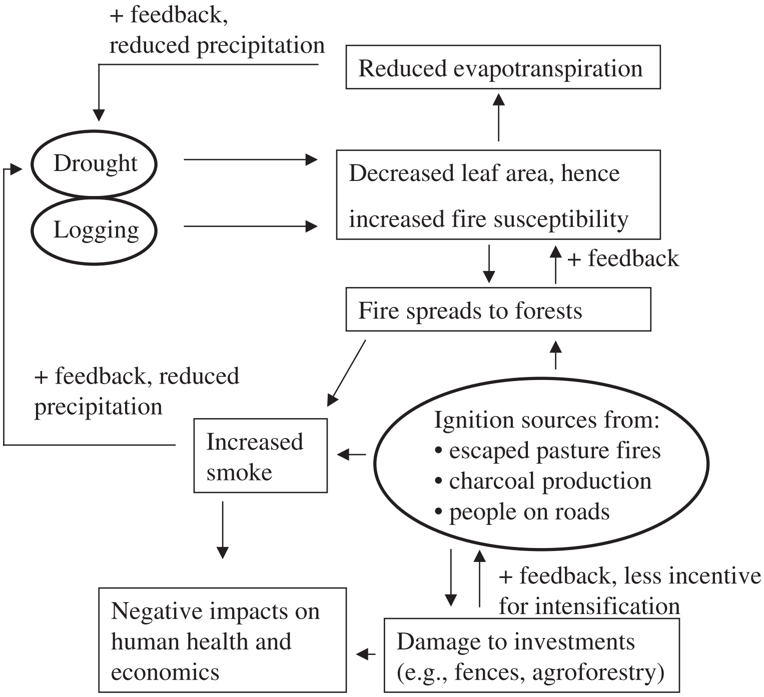

Fig. 1 Diagram of positive feedbacks of fire risk resulting from interactions among climate, logging, pasture management, and road construction. Ovals indicate exogenous forces of climate and socio-economic decisions of management. Boxes represent consequences. This diagram is based on concepts presented in Alencar *et al.* (in press), Cochrane *et al.* (1999), Nepstad *et al.* (2001, this issue), and Soares-Fihlo *et al.* (this issue).

the role of governance as a moderator of the deforestation that is expected to accompany the paving of the Cuiabá-Santerém highway. It will come as no surprise that opening and paving of roads contributes to deforestation and fire risk (Fig. 1), but Soares-Filho *et al.* (this issue) offer a novel analysis, indicating that the amount of deforestation accompanying new roads is controllable in predictable ways. They employed modeling scenarios of 'business as usual' and 'high governance,' which they defined as 'the actions by the State and civil society that protect public interests in natural resources and their utilization, including regulation, law enforcement, fiscal incentives, and the organization of informal networks of rural producers.' Under the 'high governance' scenario, where the mechanisms of sound governance *preceded* the road construction, the amount of deforestation along the road was reduced by a factor of two.

One type of change that neither Eva's new map nor Soares-Filho's model adequately addresses is the expansion of selective logging. Progress by LBA researchers on remote sensing of selective logging is reported elsewhere (Asner *et al.*, in press), and this same team reports on ground-based studies of selective logging in a pair of companion papers in this issue. Looking up at the forest canopy, Asner *et al.* (this issue, a) demonstrate that a form of carefully planned logging, called reduced impact logging (RIL), reduces canopy openness compared with conventional logging techniques. Hence, RIL can reduce the effect of logging on fire susceptibility (Fig. 1). Looking down at the soil in the same RIL experiment, Keller *et al.* (this issue) demonstrate that RIL also reduces the amount of coarse woody debris (CWD) found on the forest floor compared with conventional logging. The large amount of CWD, even on unlogged sites, was remarkable and consistent with studies elsewhere, which emphasize the importance of decay of necromass in the C balance of Amazonian forests (Saleska *et al.*, 2003; Rice *et al.*, in press).

In addition to improved land cover maps (Eva *et al.*, this issue), better maps of soils and soil properties are needed to improve regional biogeochemical modeling. Holmes *et al.* (this issue) present a sobering result from their comparison of a relatively high-resolution soils database of the Brazilian state of Rondônia with expected soil properties based on satellite-derived estimates of pasture age. Based on previous site-specific pasture chronosequence studies (Morães *et al.*, 1996; Neill *et al.*, 1997), Holmes *et al.*, expected to find a trend of an initial increase in pasture soil pH following deforestation and then a gradual decrease with pasture age, which they did, indeed, observe. However, expected changes in soil C and N stocks based on the chronosequence studies were not apparent. The issue of scale raises its ugly head once again, as the highest resolution that might be feasible for soils mapping is probably inadequate to reveal the mosaic of localized land-use change effects on many dynamic soil properties. Although soil maps and databases may not be adequate for demonstrating the impacts of land-use change, they are invaluable as inputs to biogeochemical models. While Holmes *et al*. (this issue) could not always demonstrate land-use effects at the scale of their analyses, they did demonstrate that variation of several physical and chemical properties of soils can be understood in terms of regional variation in precipitation, geological substrate, and soil age. This knowledge and these databases should contribute to our ability to understand the underlying reasons for why forest-to-pasture conversion, for example, may cause soil C increases in some climate–soil-management combinations and no change or decreases in others (Neill & Davidson, 2000).

Even at the local scale of an individual ranch, spatial variation in soil properties can confound our ability to model biogeochemical processes with mechanistically based models. Cerri *et al*. (this issue) demonstrate that the CENTURY model accurately simulated long-term trends in soil C and N stocks along a pasture age chronosequence in Rondônia, but that large variability among several young pastures could not be accurately modeled. They attributed this variation to differences among the pasture sites in their pre-clearing (forest) soil properties, whereas the chronosequence approach of substituting space for time assumes that all sites along the chronosequence were initially identical. A similar explanation of pre-existing heterogeneity may apply to the inability of Holmes *et al*. (this issue) to relate map-based estimates of soil C stocks to remote-sensing-based estimates of pasture age. Despite the problem of variation in total soil C stocks among several young pastures, Cerri *et al*. (this issue) found good agreement between modeled and observed stable isotope ratios (δ^{13}C), which provides reassurance that the model is getting decomposition of old forest-derived soil C and net inputs of new pasture-derived soil C about right.

Salimon *et al*., also used δ^{13}C to study C cycling in pasture soils in Acre, including so-called Keeling plots to determine the source of CO_2 effluxing from the soil. They demonstrated that despite the presence of considerable remnant stocks of forest-derived soil C, nearly all of the soil respiration was being produced from C_4 grass substrates. Some of the pasture soils had gained C relative to nearby forest soils, and rates of soil respiration were as high or higher in pastures than in mature and secondary forests, indicating that the grasses were allocating as much or more C belowground as the forests.

In stark contrast to the results of Cerri *et al*. (this issue) and Salimon *et al*. (this issue) in the southwestern Amazon region, Asner *et al*. (this issue, b) describe a net loss of soil C and several indicators of pasture degradation in the eastern Amazon region, near Santarém. Such contrasting results have been noted and discussed previously (Neill & Davidson, 2000), and the present studies reinforce the interpretation that responses to land-use change are dependent upon soil type and management. Hence, the scaling of soil properties demonstrated by Holmes *et al*. (this issue) could be extremely useful as input for predicting how the direction of change in soil C stocks, for example, might vary with pasture conversion across the region. More exciting, still, is the finding by Asner *et al*. (this issue, b) that indices of pasture degradation can be detected by spectral mixture analyses in Landsat imagery. The ratio of senescent foliage to live foliage increased with pasture degradation, and these types of foliage have distinct spectral properties that can be remotely sensed. Hence, areas of pasture degradation might not only be predicted from soil maps and biogeochemical models but also these predictions might be verifiable by remote sensing at local and regional scales.

Cattle pastures can be highly productive in many areas of the Amazon Basin, such as the study sites in Rondônia (Cerri *et al*., this issue) and Acre (Salimon *et al*., this issue). In addition to considerations of annual productivity, the seasonality of C uptake and evapotranspiration may also change with forest-to-pasture conversion. Salimon *et al*. (this issue) demonstrate a larger amplitude of seasonal variation in soil respiration in pasture compared with forests, with lower dry season lows and higher wet season highs in the pastures. Using eddy covariance to study total ecosystem exchange of C, water, and energy, Priante-Filho *et al*. (this issue) also demonstrate greater seasonal amplitude of these fluxes in a pasture in Mato Grosso compared with a forest. Similarly, Santos *et al*. (this issue) show very high rates of net ecosystem exchange of C and very significant seasonality in a pasture in the cerrado region near Brasília. Two important take-home messages emerge: (1) under the right soil–climate-management conditions, pastures can be extremely productive; and (2) the effects on regional climate of the increased seasonality of evapotranspiration in cattle pastures of exotic grasses compared with native vegetation may warrant further investigation (Silva Dias *et al*., 2002).

This seasonality reaches an extreme where pastures have been converted to row crop agriculture, as was the case mid-way through the study of Sakai *et al*. (this issue). During the early planning phases of LBA, it was recognized that eddy covariance towers should be placed in both forests and pastures in order to address some of the land-use questions posed by LBA. What we did not realize at that time in the mid-1990s was that corn, rice, and soybeans would also be spreading throughout the region in the early 2000s. The pasture study site near Santarém was converted to rice, which gave the Sakai team an unexpected additional treatment to study. During the peak of rice growth, its rate of net ecosystem uptake of C exceeded that of the pasture, and 50% of precipitation was returned to the atmosphere as evapotranspiration. Not surprisingly, ET fell and the site became a net source of C to the atmosphere after harvesting and plowing. This unplanned foray of LBA into the study of intensive agriculture in the Amazon Basin marks the beginning of refocused attention on this important recent trend.

Just as Martens *et al*. (this issue) addressed the difficulty of interpreting eddy covariance data in the forest, Acevedo *et al*. (this issue) also addressed this problem in the same pasture studied by Sakai *et al*. (this issue). Rather than using Martens' approach with radon, Acevedo *et al*. (this issue) used tethered balloon soundings to estimate the nocturnal boundary layer thickness, which, when combined with CO_2 concentrations, can be used to calculate a nocturnal CO_2 flux. Uncertainties remain large, but the approach holds promise for estimating fluxes during calm nights, which tend to be the rule rather than the exception in this region.

Amazônia as a regional entity

Can the simultaneous processes of wetland and riverine emissions, native forest growth, forest clearing, selective logging, intentional and accidental fire, pasture creation and maintenance, pasture degradation, small holder agriculture, and conversion to large-scale row-crop agriculture be assimilated into a single integrative framework? Hirsch *et al*. (this issue) do not include all of these processes in their ambitious modeling effort that wraps up this thematic issue, but they attempt to include many of them. Including estimates of both C release from deforestation and C sequestration during secondary forest regrowth, they estimate a net release of C to the atmosphere ranging from 0.15 to 0.35 $\mathrm{Pg\,C\,yr^{-1}}$.

Compiling new estimates based on results presented in this LBA thematic issue and other related estimates in the literature, we can compare the relative importance of basin-wide net exchange between the biosphere and the atmosphere of CO_2, CH_4, and N_2O, for both the forested state and in a changing landscape (Table 1). The emissions of CH_4, and N_2O are at least two orders of magnitude lower than net CO_2 fluxes, but the 100-yr integrated global warming potentials (GWP) of CH_4, and N_2O are about 23 and 296 times greater than CO_2, respectively (Ramaswamy *et al*., 2001). The GWP of CH_4 emissions from Amazonian wetlands and N_2O from Amazonian *terra firme* forest soils sum to about +1.3 $\mathrm{Pg\,CO_2}$ equivalents $\mathrm{yr^{-1}}$, which is of the same magnitude but opposite in sign to the estimated CO_2 sink (−1.5 to−2.2 $\mathrm{Pg\,CO_2\,yr^{-1}}$) due to growth of

Table 1 Estimates of net exchange of CO_2, CH_4, and N_2O from the Amazon Basin to the atmosphere

Source/sink	Annual basin-wide flux	Global warming potential; CO_2 equivalents ($\mathrm{Pg\,CO_2\,yr^{-1}}$)	Reference
Old-growth forest aboveground biomass	−0.4 to −0.6 Pg C	−1.5 to −2.2	Malhi *et al*. (this issue), Baker *et al*. (2004), Malhi & Phillips (2004)
Change in biomass C due to deforestation and reforestation	+ 0.15 to + 0.35 Pg C	+ 0.5 to + 1.3	Hirsch *et al*. (this issue)
CH_4 emissions from wetlands	+ 25 Tg CH_4−C	+ 0.7	Melack *et al*. (this issue)
CH_4 uptake by upland soils	−1 to −3 Tg CH_4−C	−0.02 to −0.07	Steudler *et al*. (1996), Verchot *et al*. (2000)
Change due to CH_4 emissions from cattle, biomass burning, and pasture soils	+ 3 Tg CH_4−C	+ 0.07	Steudler *et al*. (1996)
N_2O emissions from forest soils	+ 1.2 to + 1.3 Tg N_2O−N	+ 0.6	Davidson *et al*. (2001), Melillo *et al*. (2001)
Change in N_2O soil emissions due to land use change	−0.02 to −0.08 Tg N_2O−N	−0.01 to −0.04	Melillo *et al*. (2001), Verchot *et al*. (1999)

Positive values indicate emissions from the biosphere to the atmosphere, and negative values indicate uptake of atmospheric gases by the biosphere.

aboveground biomass of old-growth Amazonian forests (Table 1). The effects of land-use change must be added to this balance. Forest-to-pasture conversion has created only a relatively small net source of CH_4 and a small decrease in the source of N_2O, but has caused a substantial net release of CO_2 that is also estimated in the range of $+0.5$ to $+1.3\,\mathrm{Pg\,CO_2\,yr^{-1}}$ (Table 1).

Several potentially important fluxes are not included in Table 1. The estimates of an aboveground forest biomass sink do not include coarse woody debris (CWD). Saleska *et al.* (2003) have shown that decay of CWD can exceed live biomass growth when a site has experienced an apparent climatic disturbance in the recent past, but the distribution of previous disturbances and their effects on CWD sources or sinks of C are poorly understood. Potential gains in forest soil C are also not included in Table 1, but it appears unlikely that this could be an important sink. First, radiocarbon data for soils sampled near Manaus in 1986 and 2000 showed no evidence of C accumulation (Telles *et al.*, 2003). Second, most C allocated belowground enters rapidly cycling pools (Trumbore *et al.*, 1995; Trumbore, 2000), and so increases of even 25% in belowground net primary productivity would result in modest changes in soil C stocks (Telles *et al.*, 2003). Similarly, if all Amazonian pasture soils gained C at the rate reported by Cerri *et al.* (this issue) for the well-managed, relatively fertile soils of Rondônia, a basin-wide sink on the order of $0.15\,\mathrm{Pg\,CO_2\,yr^{-1}}$ might be expected. This value is likely partially offset, however, by soil C losses from a significant fraction of pastures that are poorly managed and degraded (Asner *et al.*, this issue; Neill & Davidson, 2000).

Some potentially important aquatic processes also are not included in Table 1. Changes in CH_4 emissions from wetlands due to land-use change and the construction of dams could be significant (Fearnside, 2002). Evasion of CO_2 from Amazonian rivers has been estimated at $0.5\,\mathrm{Pg\,C\,yr^{-1}}$ (Richey *et al.*, 2002; equivalent to $1.8\,\mathrm{Pg\,CO_2\,yr^{-1}}$). However, this is not a net emission to the atmosphere from the entire basin, because nearly all of the CO_2 emitted from the water comes from C that was assimilated by plants on land or in the water. In contrast, CH_4 that is emitted from wetlands is also derived from C assimilated by plants, but because it was assimilated as CO_2 and then released back to the atmosphere as radiatively more potent CH_4, the net effect is net production of global warming potential. Hydrologic transport of dissolved organic C (DOC) to the ocean is also not included because it would constitute a net biosphere sink only if it could be shown that it is not later metabolized.

Although emissions of VOCs are usually only a few percent of gross primary productivity, these precursors of ozone production could have important implications for calculations of warming potentials. However, estimates of basin-wide net ozone production are beyond the scope of this analysis and are not included in Table 1.

This summary indicates that the major fluxes from the intact forest-river system are likely nearly balanced in terms of total global warming potential (GWP). Even if the old-growth forest is growing as Malhi *et al.* suggest, the forest–river system converts sufficient C and N to the radiatively potent gases, CH_4 and N_2O, to counter more than half the CO_2 uptake in terms of GWP. If the estimates of Hirsch *et al.*, are correct regarding the net effects of deforestation and reforestation on C balance, then the net GWP from biological processes within the basin would be nearly balanced at about zero.

Of course, a great deal of uncertainty remains for each of these estimates, both for the fluxes per unit area and the total area over which fluxes should be extrapolated. Savanna vegetation covers about 13% of the area within the hydrologic basin of the Amazon River (Melillo *et al.*, 2001). On the other hand, the ecological region that is often described as Amazonian forest extends to other river basins, such as parts of the Tocantins, Orinoco, and various rivers in the Guianas and Surinam. A potentially significant error can arise when regional extrapolations are compared by authors who use different definitions of 'Amazônia' and its areal extent. For example, Melillo *et al.* (2001) extrapolated forest soil N_2O emissions over an area that is 80% of the area used by Malhi & Phillips (2004) to extrapolate their forest biomass carbon sink.

This collection of papers clearly demonstrates the tremendous variability that exists within Amazônia, thus underscoring the need to include this variation as an integral part of regional extrapolation. Hirsch *et al.* (this issue) put it succinctly regarding their own sensitivity analysis: 'the uncertainty in the net [C] flux due to land cover change in the Amazon will only be decreased with more precise and geographically distributed measurements of mature forest biomass and C dynamics, of the type being collected as part of the LBA-Ecology project. Using a mechanistic model will not achieve this goal on its own, if the model inputs and parameters are uncertain.'

Models of any type will be limited by uncertainties of the input data that they use, their mathematical representations of mechanisms, and parameterizations of those mechanistic equations. Likewise, a compilation of regional fluxes derived from a combination of measurements and model outputs (Table 1) is only as reliable as the studies that it summarizes. Despite the uncertainties of the offered estimates, which have become possible only through gradual accumulation of experience and knowledge of the type that the LBA project fosters, such syntheses advance our science. The summary in Table 1 will serve its purpose if it fosters more curiosity that leads to more work that can be used to re-evaluate this synthesis. The twenty-six papers presented in this LBA thematic issue demonstrate the tremendous progress, and also large remaining hurdles, in narrowing the uncertainties in our understanding of how Amazônia functions as a regional entity in the Earth system, both now and as humans continue to expand their influence in the region.

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