Results From LBA and a Vision for Future Amazonian Research

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This chapter summarizes selected results from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) and briefly describes a vision for future Amazonian research. The need for research on people and environment interactions is emphasized in the context of regional and global change. LBA developed institutional and scientific capacity in Amazonia, but its performance to promote sustainable development was restricted because the program has predominantly emphasized the advancement of basic knowledge, with less emphasis on integrative studies explicitly designed to influence public policies with consequences on land use and land cover. The challenge of transforming the natural goods of Amazonia into human and economic benefits in an environmentally sustainable manner requires a new level of consciousness and collaborative work through the ability to move from simple diagnosis in the direction of actions at local, regional, and national levels. From the results of LBA, we may evolve to new experiences in which society will add value to the interactions between the biosphere and the atmosphere.

1. INTRODUCTION

Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) research has been steered by the recognition that Amazonia is undergoing a rapid and intense transformation associated with the processes of development and occupation. Changes in land use, land cover, and climate can affect the biological, chemical, and physical processes as well as the sustainable development of the region and its interactions with the regional and global climate. The journey through the chapters of this book confirms that LBA is a multidisciplinary program seeking to understand the functioning of Amazonian ecosystems and Amazonia as a regional entity of the Earth system. It also seeks to understand causes and consequences of the ongoing changes in the region and how to minimize impacts from its development.

The original scientific agenda of LBA was designed around two overarching questions that are addressed through multidisciplinary research: (1) How does Amazonia function as a regional entity? (2) How will changes in land use and climate affect the biological, chemical, and physical functioning of Amazonia, including the sustainability of the region and the influence of Amazonia on regional and global climate?

Since the launching of the program in the 1990s, much has been accomplished to answer these questions, but much still has to be done through and beyond LBA science. This chapter summarizes lessons from LBA and briefly describes a vision for future Amazonian research.

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2. SELECTED RESULTS FROM LBA

Since its beginning, LBA has produced countless publications, including more than 2000 articles in indexed journals, more than 200 book chapters, at least 13 books, and 10 special issues of scientific journals (*Journal of Geophysical Research*, *Remote Sensing of Environment*, *Ecological Applications*, *Global Change Biology*, *Theoretical and Applied Climatology*, *Acta Amazonica*, *Earth Interactions*, *Hydrological Processes*, *Atmospheric Chemistry and Physics*, and the *Brazilian Journal of Meteorology*). It is virtually impossible to enumerate all the findings produced by LBA, but the following paragraphs highlight selected achievements, as summarized in the LBA2 science plan [*Batistella et al.*, 2007].

Amazonia can be categorized as a region with high environmental and social risks as far as climate change and variability are concerned. The risks are not only due to the predicted climate change, but also to the process of occupation of the region, including deforestation and changes in land use. Models indicate the possibility of the occurrence, in the next decades, of an abrupt and irreversible replacement of forested areas by vegetation with lower biomass content, affecting biodiversity and the livelihoods of regional populations.

2.1. Physical Climate System

In the context of climate change [*Marengo et al.*, this volume], projected scenarios until the end of this century indicate possible reductions of up to 40% of rainfall and increases of temperature of up to 8°C [*Marengo et al.*, 2007]. The most severe impacts on the redistribution of species and biomes would be felt in northeastern Amazonia, with less severe impacts in western Amazonia [*Salazar et al.*, 2007].

Changes on land use have major effects on the meteorology of Amazonia [*Nobre et al.*, this volume; *Betts et al.*, this volume; *Silva Dias et al.*, this volume; *da Rocha et al.*, this volume]. In Rondonia, westerly and easterly intraseasonal wind oscillations were observed associated with different characteristics of rain, composition of aerosols, and cloud condensation nuclei. The extensive hydrological system of Amazonia affects the atmospheric circulation and the circulation pattern at the interface of large rivers with neighboring forest [*Silva Dias et al.*, 2004]. Large areas of open water produce regional circulations that change the distribution patterns of clouds and the daily profile of winds at the forest-river interface, including alterations to the carbon flux in areas near large Amazonian rivers. Deforestation and changes in land use also influence cloud cover at seasonal scales and diurnal distributions [*Durieux et al.*, 2003]. In the dry season, observations showed more low-level clouds in the early afternoon and less convection at night and in early morning over deforested areas. During the wet season, convective cloudiness is enhanced in the early night over deforested areas [*Machado et al.*, 2004].

2.2. Atmospheric Chemistry

The effect of aerosols on the functioning of the Amazonian ecosystems was also extensively studied in LBA using several approaches [*Kesselmeier et al.*, this volume; *Longo et al.*, this volume; *Artaxo et al.*, this volume; *Davidson and Artaxo*, 2004; *Artaxo et al.*, 2006]. The impact of trace gases and aerosol emissions from biomass burnings in Amazonia was also quantified [*Artaxo et al.*, 2002], and its effects are not limited to Amazonia, but reach a large portion of the South American continent. A strong influence of aerosol particles was observed on mechanisms of formation and development of clouds [*Andreae et al.*, 2004] with important implications for the hydrological cycle. Cloud suppression and a decrease in size of cloud droplets in areas with high concentration of aerosols were also observed. The residence time of clouds is increased in the presence of large amounts of aerosols, which potentially reduces local precipitation and alters the radiation balance. New mechanisms of natural formation of clouds were observed with the production of cloud condensation nuclei from volatile organic compounds emitted by vegetation [*Clayes et al.*, 2004]. The aerosols emitted through biomass burning can intercept large amounts of solar radiation significantly altering the radiation balance. These particles also affect photosynthetic rates for forested areas far from the biomass-burning region, strongly influencing carbon cycling in Amazonia.

2.3. Biogeochemistry: Carbon Storage and Exchange, Other Trace Gases, and Nutrients

LBA has also conducted intensive studies into biogeochemical cycles [*Davidson and Martinelli*, this volume; *Luizão et al.*, this volume; *Bustamante et al.*, this volume; *Malhi et al.*, this volume; *Phillips et al.*, this volume; *Saleska et al.*, this volume; *Houghton et al.*, this volume; *Meir et al.*, this volume; *Trumbore and de Camargo*, this volume; *Lloyd et al.*, this volume]. The cycling of nutrients such as phosphorus and nitrogen is critically important for ecosystems. The mechanisms and quantification of carbon cycling is one of the key scientific areas of LBA. The answer to the question if Amazonia is a source or a sink of carbon still remains open. But LBA has already produced important results about the mechanisms that regulate the carbon fluxes in natural ecosystems and in areas disturbed by land use changes. Research conducted throughout Amazonia showed a trend of forest growth and biomass accumulation [*Malhi et al.*, 2004]. This trend is especially stronger in western Amazonia, but its cause remains unknown [*Baker et al.*, 2004]. LBA has put in place a set of flux towers with semicontinuous operation over many years. The results of the flux towers also showed a predominant trend of carbon sink across several locations with some interesting examples of sites showing ecological disturbance as noticed in large quantities of aboveground dead biomass [*Saleska et al.*, 2003]. These flux studies have also changed our conception about the seasonality of carbon fluxes in Amazonian forests. Several sites showed greater net carbon uptake during the dry season in comparison with the wet season, most likely due to the water availability in deep soils and larger photosynthetic radiation during the dry season [*Silva and Avissar*, 2006]. The knowledge of nutrient cycling is critical to the recovery of degraded areas in Amazonia. *Davidson et al.* [2007] described the complex mechanisms involved in phosphorus and nitrogen balance in chronosequences of vegetation recovery. It was observed that it takes at least 70 years to reestablish the nitrogen cycle after disturbance.

2.4. Land Surface Hydrology and Water Chemistry

Other studies demonstrated that land use and land cover changes, such as forest conversion to pastures, significantly alter the physical and chemical characteristics of rivers affecting their structure and functioning [*Richey et al.*, this volume; *Tomasella et al.*, this volume; *Melack et al.*, this volume; *Costa et al.*, this volume]. When the forest is removed, the light availability favors the increase of water temperature and influences a series of chemical reactions such as the oxygen solubility [*Neill et al.*, 2006]. The replacement of primary vegetation by pastures also enhances erosive processes [*Thomas et al.*, 2004; *Krusche et al.*, 2005]. Larger contributions of labile organic material cause an increase in the process of decomposition that is dependent on dissolved oxygen in water [*Bernardes et al.*, 2004]. As a consequence, there is a decrease in the oxygen concentration with impacts on the biota. The nitrogen cycle is also affected since the available quantity of nitrogen decreases in pastures, thus decreasing its availability to small rivers, which become deficient for nitrogen and not for phosphorous as they were originally [*Carmo et al.*, 2005]. However, there are uncertainties as to whether these changes are extended to higher-order rivers, mainly those which drain mesoscale hydrological basins.

2.5. Land Use and Land Cover

Important advances were made through land use and land cover studies in LBA, as posed by the original research questions [*LBA*, 1996; *Alves et al.*, this volume; *Asner et al.*, this volume; *Schroeder et al.*, this volume]. In addition, new monitoring techniques, executed directly or indirectly within LBA, allowed the development of studies at different temporal and spatial scales, particularly concerning forested areas.

During the entire period of LBA implementation, surveys on annual deforestation were conducted by the Brazilian National Institute for Space Research, which provided the scientific community with important information on rates and patterns of deforestation [*Alves*, 2002]. They also allowed LBA to identify new questions regarding local and regional patterns of land use, particularly regarding the dynamics of occupation in pioneering zones [*Batistella and Moran*, 2005], the dynamics of forest conversion to intensive agriculture [*Morton et al.*, 2006], and the relationship between logging, forest degradation, and conversion rates [*Asner et al.*, 2005a; *Souza. et al.*, 2005]. Other studies indicated a variety of processes not only related to the expansion of agricultural frontiers but also to the intensification of land use and variations on production systems based on traditional and modern technologies. This work was conducted at several sites by means of robust remote sensing techniques and field work [*Roberts et al.*, 2003; *Lu et al.*, 2004]. The destiny of abandoned areas and their potential environmental services became extremely relevant, despite the evidence showing the reduction of these areas in extremely degraded regions [*Alves et al.*, 2003].

A significant advance was made in understanding the intensity and extension of logging in Amazonia as well as the possible environmental damage caused by this activity [*Chambers et al.*, 2001]. *Nepstad et al.* [1999] found that areas under logging activities are equivalent in extension to areas deforested annually. Approximately 16% of logged areas are converted to deforested area in the following year, and about 32% are deforested within 4 years. This means that logging does not occur prior to deforestation, but it is a way of disturbance in itself, facilitating the increase of impacted areas by human activities [*Asner et al.*, 2005b].

Therefore, changes in land use can affect the environmental services, especially those related to the long-term functioning of ecosystems [*DeFries et al.*, 2004]. The long-term changes were assessed by *Foley et al.* [2007] through analysis of various LBA results. The authors indicated four examples of environmental services negatively affected by deforestation and degradation: carbon storage, hydrological flux, the influence on the regional climate, and disease vectors.

Within plausible scenarios for changes in land use and land cover in Amazonia, analytical and theoretical tools were developed with the purpose of feeding regional climatic

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models including governance alternatives to current land use dynamics [*Soares Filho et al.*, 2006].

2.6. Human Dimensions

Significant efforts were made in research on the human dimensions of environmental change in Amazonia within LBA [*Walker et al.*, this volume; *Perz et al.*, this volume; *Pfaff et al.*, this volume; *Brondizio et al.*, this volume; *Batistella et al.*, 2008]. Initially, ad hoc partnerships were encouraged to discuss scientific questions identified by the program community, in particular those aimed at reaching a better understanding of the processes of land use and land cover change. This action catalyzed the construction of more solid bridges with social scientists starting from their insertion into the LBA Science Steering Committee and, eventually, through systematic or programmatic initiatives. Among these initiatives, a survey of scientific production on Human Sciences, seminars and courses featuring the theme, and several publications can be considered the most significant results of the component on human dimensions of LBA [*da Costa et al.*, 2007].

2.7. Training and Education

Besides the scientific production, the training and education activities are recognized as one of the major results and legacies of the program. More than 900 students were trained, including undergraduate, master, and doctorate students. In order to improve training of young scientists engaged in LBA, the Brazilian Council for Research (CNPq) created a special scholarship program. Three undergraduate, four master, and two doctorate courses were originated within LBA, all of them in Amazonian states. In addition to the scientific motivation, these human resources, now available in the region, represent a positive and crucial factor toward a new vision for Amazonian research.

3. BEYOND SCIENTIFIC BARRIERS: PEOPLE, ENVIRONMENT, AND INTEGRATIVE RESEARCH IN AMAZONIA

The first phase of LBA tended to favor some research sites due to historical considerations and the experimental design based on ecological transects. Therefore, large areas and other important environments were underrepresented. It is important now to review the geographic distribution of LBA efforts, seeking to balance the research planning, based on ecological and biogeographical aspects. This is vital for the integration of local, regional, and global studies.

Basic environmental research must go on, but it is also crucial to build new bridges for applications on sustainable development [*Batistella and Luizão*, 2006]. The focus should continue to be the region as a whole, but with case studies in priority areas. For those integrated studies, a new research configuration is proposed, based on three disciplinary domains.

One of these domains is being structured as "multiscale physical-chemical interactions on the biosphere-atmosphere interface." Its objective is to study the transportation and transformation of water, energy, trace gases, and aerosols in the Amazonian system and to identify the effects and impacts of human activities in the region. It is necessary to have a strong connectivity between the production of knowledge and its applications to the sustainable development, including technological innovations in cattle ranching, productive arrangements and chains, environmental predictions, and impacts on the human population. A second domain deals with the "social dimensions of the environmental changes and the dynamics of land use and land cover," with studies on the complex interactions between the environment and the society that characterizes the region. The third domain deals with "physical, chemical, and biological processes of aquatic and terrestrial systems and their interactions." Therefore, the issue on the environmental development strategies associated with sustainable practices of production becomes one of the important topics.

Within those disciplinary domains and after an extensive discussion with decision makers, stakeholders, and the scientific community, three research themes united the main questions to be addressed during the second phase of LBA: (1) the Amazonian environment in transformation; (2) the sustainability of environmental services and the systems of terrestrial and aquatic production; and (3) the climatic and hydrological variability and its dynamics: vulnerability, adaptation, and mitigation.

An analysis of the results, to date, and the identification of remaining gaps reveal the need for regionalization through mesoscale integration. In particular, processes such as land degradation and land use intensification need to be studied and monitored using integrative approaches linking social and natural sciences. In this way, one can begin to construct empirically based real-time approaches to policy making for Amazonia. We suggest the following actions as beneficial to the region, based on LBA science: (1) generation of products at regional scale on land cover change based on multisensor observations; (2) integration of biophysical data with the demands of social and economic agents, e.g., through zoning and territorial planning making use of science in management; and (3) modeling of the spatial distribution of deforestation, land degradation, and land use intensification and mapping vulnerabilities both biophysical and social.

To ensure the use of science in policy making and provide modeling with usable characteristics, it is important as we move forward in LBA: (1) to standardize data collection whether at household or less detailed scales of aggregation; (2) to choose models that permit proactive engagement of agents and other decision makers, not just scientists; and (3) to promote interaction among the scientists of LBA, cutting across fields such as biogeochemistry, land change, social interactions, atmospheric chemistry, and regional climate models.

Also, training and education of young researchers as well as their engagement in local institutions will contribute significantly to enhance the capacity of Amazonians to lead and conduct studies about the functioning of ecosystems and its importance in the context of global change.

There is a fundamental need to shift between regional analyses and case studies, as public policies based only on studies at regional scales may hide important sustainable practices. Moreover, the understanding of the characteristics, drivers, and consequences of land change in Amazonia should not depend only on land use and land cover studies per se but must include analyses of the human dimensions of environmental change.

The scientific community is engaged in a broad and participatory discussion on how to make the transition to the next decade of Amazonian research. For example, the Brazilian government, through the Ministry of Science and Technology, is coordinating the effort to advance from the recognized success of the first phase of the program to the new phase of LBA, a challenging undertaking on integrative regional studies including complex linkages with global change issues.

Much has to be done for LBA to progress from its multidisciplinary research to interdisciplinary and transdisciplinary integrative questions. In particular, it is vital to link local and regional processes with global change issues through mesoscale integration. Land use and land cover changes should still be at the core of the program because of their role in landscape transformation and consequent impacts on carbon dynamics, biogeochemical cycles, hydrological processes, atmospheric chemistry, and the physical climate. Recent processes in Amazonia, such as urbanization, agriculture intensification, and forest management should be of particular interest as they drive new changes to the region.

An integrated perspective provides a rare opportunity to understand Amazonian ecosystems, landscapes, and regions using a research strategy advocated by IGBP Phase II scientists [*Moran et al.*, 2004]. This new science strategy views human-environment systems as integrated multiscaled systems and requires a new approach to scale up from case studies to the region, with particular attention to thresholds and nonlinearities. Some LBA investigations have contributed to an integrative research agenda, through dialogues between natural and social sciences. A major challenge is to capture regional differences as well as to understand local-scale dynamics [*Batistella and Brondizio*, 2004; *Batistella and Moran*, 2007; *Lahsen and Nobre*, 2007]. A more complex framework for LBA research then arises, indicating the need for a continuous search for linkages between land use/land cover changes and other processes. LBA is initiating a new programmatic effort that will be essential to enhance its interface with other research initiatives. The recognition of continuous and creative reviews on the integration of social and natural sciences is among the incentives for a science of sustainability in Amazonia.

4. INSTITUTIONAL CONCERNS: A VISION FOR THE FUTURE

Under the concept of institution building, we include a discussion about the social and environmental dimensions of change in Amazonia, as well as the articulation between the scientific and political domains. The role of communities in the management of natural resources and the challenges of institutional development has received special attention. The articulation between science and policy making is a necessary step to respond to environmental change, taking advantage of concepts and results produced by LBA.

The term "sustainability science" has been created to describe research aimed at facilitating the transition to sustainability. Focusing on the interaction between environmental sciences and science of development, science for sustainability is driven by the concern for the welfare of people and life on the planet, seeking to combine research activities and to understand how human and natural systems interact from local to global scales. Science for sustainability is also an initiative to include more social sciences, the priorities of least developed countries and subglobal foci, balanced against the general trends favoring the global environmental sciences and approaches that reflect priorities of most developed countries [*Cash et al.*, 2003; *Clark*, 2007].

LBA indirectly promoted sustainability by developing the scientific and institutional capacity in the region, especially in Brazilian Amazonia, along with the fact that the knowledge and collected data can be freely accessed. The development of such capacity to face environmental change is necessary at the global level [*Ambuj and VanDeveer*, 2005], but it is especially so in less developed countries because they have fewer financial and human resources and are more

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vulnerable to multiple impacts resulting from rapid and simultaneous changes in social and environmental systems [*Kates et al.*, 2001].

However, the capacity of LBA to promote sustainable development in Amazonia was restricted because the program has predominantly emphasized the natural sciences and the advancement of basic knowledge, with less emphasis in integrative studies explicitly designed to influence public policies and actions with consequences on land use and land cover in the region. As summarized by *Batistella et al.* [this volume], some notable LBA efforts have been undertaken successfully to promote the use of Science and Technology (S&T) for sustainable development in the region. The goals of sustainability could have been better achieved with more studies of this type.

The difficulties in addressing sustainable development in the region reflect, in part, the difficulty of uniting the natural and social sciences [*Philippi et al.*, 2003; *Schor*, 2005] and of understanding the relationship between scientific thinking and decision-making processes related to the design of public policies.

Since the preliminary discussions for the development of the first scientific plan of LBA in the early 1990s, the perception about the role of Amazonia surpassed its geopolitical importance and its natural capital. Therefore, the challenge of sustainability remains. In response to worldwide growing concern about the risks of destructive environmental practices, governments have launched environmental conservation plans for the region. Amazonia's biodiversity is now seen as the basis for cutting-edge sciences, especially biotechnology and geotechnology, capable of reconciling regional development and environmental conservation. However, this set of visions and good intentions is confronted with a well-established economic process based on the exploitation of natural resources as a mean to generate development. Such process is historically supported by the implementation of infrastructure projects and incentives for extensive land use change, with great potential to maintain the cycle of deforestation.

The challenge of transforming the natural capital of Amazonia in human and economic benefits through an environmentally sustainable manner requires a new level of consciousness and collaborative work. While S&T should play a central role to meet this challenge, there is little systematic knowledge about how to create institutions to effectively use S&T for sustainability. This challenge is significantly greater for Amazonia due to the absence of a model to be copied, that is, at least one tropical developed country or region with an economy strongly based on diversified natural resources, particularly forest resources, and intensive use of S&T through an educated and trained workforce to promote development and environmental conservation [*Nobre and Lahsen*, 2008].

The solution to this dilemma depends on the ability to move from simple diagnosis in the direction of concrete, persistent, and integrated actions at local, regional, and national levels. While recognizing that much of this challenge is political, S&T have a central importance for the sustainable development of Amazonia, including the need for new knowledge about the environmental services provided by the region.

The Amazonian countries should seek to implement a new development paradigm, minimizing deleterious environmental impacts. This is a huge challenge, particularly for developing countries with social liabilities. From the results of LBA, we may evolve to new experiences in which society will add value to the interactions between the biosphere and the atmosphere.

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