The Large-Scale Biosphere-Atmosphere Experiment in Amazonia: Analyzing Regional Land Use Change Effects

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The Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) is a multi-disciplinary, multinational scientific project led by Brazil. LBA researchers seek to understand Amazonia in its global context especially with regard to regional and global climate. Current development activities in Amazonia including deforestation, logging, cattle ranching, and agriculture significantly perturb regional and global carbon budgets and the atmospheric radiation budget through both greenhouse gas inputs and the increase in atmospheric particulates generated by fires. The Brazilian Amazon currently releases about 0.2 Pg-C to the atmosphere each year as a result of net deforestation. Logging and forest fire activity are poorly quantified but certainly increase this amount by more than 10%. Fires associated with land management activities generate smoke that leads to heating of the lower atmosphere, decreases in overall cloudiness, increases in cloud lifetimes, and the suppression of rainfall. There are considerable uncertainties associated with our understanding of smoke effects. Present development trends point to agricultural intensification in the Brazilian Amazon. This intensification and the associated generation of wealth present an opportunity to enhance governance on the frontier and to minimize the damaging effects of fires.

INTRODUCTION

We present recent findings from the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) that bear on questions of the future role of the Amazon in global climate, in particular through its role in the carbon cycle, and in the modification of atmospheric processes through deforestation and fire. LBA is a multi-disciplinary, multinational scientific project led by Brazil.

LBA researchers seek to understand Amazonia in its global context. LBA studies ask how changes in land use and climate affect the biological, chemical, and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate.

Planning for LBA began in 1992 and field research programs began in 1998. LBA studies evolved from prior campaigns that investigated biosphere–atmosphere exchange and the effects of deforestation on climate and chemistry in the Amazon. Historical antecedents to LBA include the first airborne studies of biomass burning emissions in the region [*Crutzen et al.*, 1985], the Amazon Boundary Layer Experiments (ABLE) [*Harriss et al.*, 1988, 1990] and the

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Anglo–Brazilian Climate Observation Study (ABRACOS) [*Gash et al*., 1996]. Studies by *Crutzen* and others [1985] and the ABLE studies demonstrated the importance of biomass burning to atmospheric chemistry over Amazonia. The ABLE experiments established a paradigm for integrated airborne and ground based observations. ABRACOS set the stage for LBA in part through the selection of key field sites, but more importantly by contrasting biophysical functions and climatic forcings of relatively undisturbed forests with managed ecosystems.

After a half-decade of LBA field studies, we are reaching some new realizations and raising new questions about the functions of Amazonia and the prospects for sustainable development. While early planning for LBA included the full region of Amazonia, the reality of LBA to date has emphasized Brazil. This review will deal primarily with the Brazilian Amazon region although many of the findings presented would be applicable to lowland areas outside of Brazil, as well.

The Amazon is both the world's largest river and the name given to the region, Amazonia, that contains the river's hydrographic basin and adjoining forested regions of the Orinoco River Basin and the Guyanas. This vast forested area covering portions of nine countries is the largest continuous extent of tropical forest on our planet and one of the last great remaining forested habitats on Earth. Amazonia still conjures up mysterious images of primeval forest and uncontacted indigenous people. In fact, it is home to over 24 million people, most of whom live in cities and are very much a part of today's globalized society. We cannot consider Amazonia remote when in about a day one can fly to any of hundreds of airports on commercial carriers from nearly anywhere else in the word.

While no longer remote, Amazonia is still vast. The Amazon Basin proper covers 5.8 million km^2 and the river it contains has an annual discharge of nearly 6 x 10^{12} m^3 y^{-1} [*Salati and Vose*, 1984]. While most of the basin is naturally forested, a substantial portion, especially in Brazil, is covered by savanna. The Brazilian savanna biome, known in Brazil as *cerrado*, covers nearly 2 million km^2 that lies mainly outside of the hydrographic basin of the Amazon [*Oliveira and Marques*, 2002].

The Amazon region plays a significant role in global climate. From 1350 to 1570 mm y^{-1}, equivalent to 63% to 73% of the annual rainfall, evaporates or transpires at the surface [*Costa and Foley*, 1998; *Marengo and Nobre*, 2001]. In numerical experiments with global circulation models, extensive regional deforestation leads to regional declines in precipitation and could have significant teleconnections in global climate [*Nobre et al.*, 1991; *Marengo and Nobre*, 2001; *Werth and Avissar*, 2002]. In contrast to regional scale deforestation, deforestation on a mesoscale (<100 km) may lead to locally increased precipitation [*Baidya Roy and Avissar*, 2002]. This raises an important question: What is the threshold of deforestation amount and distribution beyond which precipitation will decline [*Avissar et al*., 2002]?

The Amazonian forests are mostly evergreen and highly productive despite extended periods of annual drought. Deep roots allow Amazon forests to maintain productivity through dry seasons that extend up to 5–6 months [*Nepstad et al.*, 1994]. Amazonia is also characterized by ancient geologic surfaces covered by highly weathered soils that are relatively infertile [*Irion*, 1978]. About 70% of Amazon soils are dystrophic Oxisols and Ultisols, although more fertile soils cover substantial areas particularly on river floodplains and in the western Amazon [*Richter and Babbar*, 1991]. Nutrients such as phosphorus (P) and base cations (K^+, Ca^{++}, and Mg^{++}) are relatively scarce or only slowly available in most heavily weathered Amazon soils, whereas under mature upland forests nitrogen is often abundant.

Amazonia has been inhabited by humans for at least 10,000 years [*Roosevelt et al*., 1996] and humans probably had an important role in modifying the species composition and functions of the forest ecosystem [*Heckenberger et al*., 2003]. Following the European invasion and migrations from the Old World, the indigenous population of the Amazon declined drastically [*Denevan*, 2001]. The forest undoubtedly changed as human influence waned and waxed.

Today's mode of forest exploitation depends on the extensive use of a nineteenth century technology, the internal combustion engine, coupled with more recent communications technologies that link Amazonia to national and global economies. Internal combustion engines powering chain saws, crawler tractors, and trucks have changed the dynamics of penetration into the Amazon's interior. Previously, waterways provided the prime means for moving people and goods. Today, roads mark a template for rapid forest exploitation. In Brazil, forest clearance and agricultural development was catalyzed by the opening of the Belém–Brasilia Highway in the 1960's and accelerated enormously in the 1970's and 1980's with the construction of roads such as the Trans–Amazon Highway and BR-364 in Rondônia. For three major highways (BR-010, PA-150, and BR-364) paved between 1965 and 1980, *Nepstad et al*. [2001] showed that 41% of the forest within 100 km of these roads had been deforested by 1992. Almost all of the deforestation (92.4%) that occurred between 1991 and 1997 took place within 100 km of major, although not necessarily paved, roads [*Alves*, 2002].

Recent trends in land use in Brazil indicate consolidation of the old frontiers, a new phase of experimentation in land management, and a heightened level of governance [*Carvalho et al*., 2002]. Added to the old mixture of logging, cattle ranching, and subsistence cropping is a move toward more intensive management including mechanized production of grains, dairy cattle, and agro-forestry products [*Carvalho et al*., 2002]. The old style of development is closely connected to the use of fire. As seen in the El Niño of 1997–1998, under drought conditions fires on managed land can escape to logged and even intact forest causing extensive tree mortality [*Cochrane et al*., 1999]. Logging continues to expand as a predatory activity where valuable species are removed, and little or no attention is paid to future timber production. The expansion of logging leads to more open canopies that leave normally non-flammable forests susceptible to fire [*Nepstad et al*., 1999a]. The potential for fire to spread from deforested areas into fragmented forests represents a threat to long-term ecosystem health and sustainability [*Cochrane et al*., 1999; *Nepstad et al*., 1999a; *Cochrane and Laurance*, 2002].

AMAZONIA AND THE CARBON CYCLE

The extensive forests of Amazonia hold a vast repository of carbon. The Amazon forest vegetation in Brazil alone contains about 70 Pg of carbon (C), between 10% and 15% of global biomass [*Houghton et al.*, 2001] on only 3% of the land area. The total biomass of Amazon forests is poorly known because accurate surveys are limited [*Brown et al.*, 1995; *Houghton et al.*, 2001; *Keller et al.*, 2001; *Malhi et al.*, 2002]. *Houghton et al*. [2001] compiled seven regional estimates of biomass for forests in the Brazilian Legal Amazon region that range from 39 to 93 Pg-C (carbon densities of 98 to 233 Mg-C ha^{-1}).

Carbon Flux in Undisturbed Forests

The biomass of Amazonia is not static. In recent years, several studies using eddy covariance [e.g., *Grace et al*., 1995; *Malhi et al*., 1998; *Andreae et al*., 2002] and biometry [*Philips et al*., 1998] have indicated that mature forests throughout the Amazon are gaining carbon at rates from 0.5 to 6 Mg C ha^{-1} y^{-1}. Even at the low range of these estimates, the implied carbon uptake for all Amazon forests would be significant at a global scale. However, there are reasons to question the reliability of both the eddy flux and biometric results. Recent estimates from the Tapajos National Forest near Santarem, based on both eddy covariance and biometry measurements, show that at least some forest sites are losing carbon to the atmosphere [*Saleska et al*., 2003; *Miller et al*., 2004; *Rice et al*., 2004]. *Saleska et al*. [2003] and *Miller et al.* [2004] clearly demonstrate the need to correct for the effect of nocturnal stability of the atmosphere on eddy flux results from tropical forest sites. Correction for the effects of nocturnal stability makes extremely high net carbon uptake values such as 6 Mg-C ha^{-1} y^{-1} [*Malhi et al*., 1998] extraordinarily unlikely. In a comparison between flux measurements by eddy covariance with simultaneous measurements by the boundary layer budget approach made over the same site, *Lloyd et al*. [submitted] showed that the large apparent uptake of CO_2 by the forest was the result of the nighttime respiration flux being severely underestimated by the eddy approach.

Saleska et al. [2003] and *Rice et al.* [2004] also question the results of short-term biometric studies. They point out that coarse woody debris serves as important carbon reservoir in the tropical forest that they studied. If coarse woody debris had not been accounted for in their biometric studies, then the forest plots would have appeared to be gaining 1.4±0.6 Mg-C ha^{-1} y^{-1} whereas complete biometric measurements coupled with estimates of decomposition show that the same plots are losing -2.0±1.6 Mg-C ha^{-1} y^{-1} [*Saleska et al*., 2003]. At these sites, a large stock of coarse woody debris, presumably the result of a relatively recent disturbance, emits -5.7±1.0 Mg-C ha^{-1} y^{-1}. Most of the above-ground carbon uptake occurs in the smaller size class trees giving additional credence to the hypothesis that the site was recently disturbed. Certainly, all of the sites studied by *Philips et al*. [1998] would not fit this pattern. But, for greater confidence in accounting for carbon balance, unless coarse woody debris and its decay is accounted for, it would be prudent to exclude plot records shorter than the lifetime of coarse woody debris in lowland moist tropical forests (approximately 5–7 years).

Resolution of the question of whether old growth forests of Amazonia are losing or gaining carbon requires a larger scale approach. Two possible approaches are biometric and inversion of atmospheric transport models using measured carbon dioxide concentrations. Large numbers of randomly located forest plots stratified to cover all important forest types would ideally fulfill the biometric need. The RAINFOR project [*Malhi et al*., 2002] has collected data on existing plots and has expanded the network of plot data available across the Amazon. While this network is still relatively small, it represents the most extensive network of Amazon region plots assembled to date. Plans exist within LBA for aircraft measurements of carbon dioxide within the Amazon region. Frequent profile measurements at coastal and interior sites would greatly improve regional estimates of carbon exchange. Inverse model approaches would quantify a regional carbon budget that includes the net effects of the various fluxes including deforestation, logging, fire, secondary regrowth and the possible increase in biomass of growth forests. Therefore, plot based and atmospheric approaches are best conducted in parallel.

Carbon and Other Greenhouse Gas Fluxes Resulting From Land Use Change

Land use change and deforestation lead to a substantial net flux of carbon from the biosphere to the atmosphere. Conversion of forest to pasture has been the most common change in land use in the Brazilian Amazon. Brazil is unique among the nations of the world because it monitors these changes annually using satellite remote sensing. Using Brazilian government statistics (http://sputnik.dpi.inpe.br:1910/col/dpi.inpe.br/vagner/2000/05.18.16.34/doc/index.html) and independent measurements, we know that the average rate of deforestation in the 1990's was approximately 20,000 km^2 y^{-1} [*Houghton et al.*, 2000]. According to *Houghton et al.* [2000], the annual clearing rate is known to an accuracy of about 25%. The carbon exchange from deforestation depends upon the biomass density in the deforested area. As noted above, biomass density is poorly constrained for the Brazilian Amazon. Moreover, while the existing maps of biomass density analyzed by *Houghton et al.* [2001] converge on a total biomass of about 177 Mg-C ha^{-1}, these maps disagree in estimation of the spatial distribution of the biomass. Deforestation has been spatially concentrated in many regions where there are scarcely any biomass measurements (e.g. near the forest-*cerrado* boundary in Mato Grosso and southern Pará). Transfer of carbon to the atmosphere in any given year depends upon the amount of carbon lost in clearing fires [c.f. *Potter et al.*, 2001; *van der Werf et al.*, 2004] and the rate of decay of coarse wood left behind in pastures and fields after clearing fires. *Houghton et al.* [2000] estimated that this biosphere–atmosphere transfer for the Brazilian Amazon is about 0.3 Pg-C y^{-1}, with an allowance for error of about 60%, primarily because of the unknown biomass density term.

Clearing of forest may be balanced in part by regrowth of secondary forests. Regrowth rates vary widely by location and depend on a variety of factors including dry season length, soil type and fertility, and prior land use intensity [*Johnson et al.*, 2000; *Moran et al.*, 2000; *Uhl et al.*, 1988; *Uhl et al.*, 1982]. Regrowth is frequently recycled through shifting cultivation or as the result of changing economic conditions such as the availability of credit or the price of commodities such as beef [*Moran et al.*, 1996; *Alves et al.*, 2003]. Despite the potential for large carbon sinks in young secondary succession, the total carbon sink from this secondary forest regeneration was estimated by *Houghton et al.* [2000] as about 0.02 Pg-C y^{-1} for the Brazilian Amazon. Land clearing and conversion of native vegetation to agricultural use, particularly under tillage, generally leads to substantial losses of soil carbon (average of 30%) [*Davidson and Ackerman*, 1993]. If large areas are tilled as a result of expanding grain production in the Amazon region, the future carbon balance may be affected. Currently, in the Amazon region, relatively little land is tilled. Following the conversion of forest to pasture, soils may gain carbon under careful management or lose carbon where management is poor [*Neill and Davidson*, 2000]. In any case, these soil carbon changes are likely to be small compared to the large quantities of carbon lost from the destruction of forest biomass.

When considering atmospheric radiative effects, the conversion of forest to pasture has a number of secondary effects. The first of these is the use of fire to maintain pastures. Even if all of the CO_2 liberated in fires is later taken up by pasture regrowth, the releases of other gases and particulates have important radiative effects. We will discuss particulates in smoke in the section below. Pasture management changes the fluxes of the biogenic greenhouse gases, methane and nitrous oxide. Methane (CH_4) is released by fires, by grazing cattle, and slightly by pasture soils [*Steudler et al.*, 1996]. The conversion of forest to pasture also subtracts the lost effect of soil methane uptake [*Keller et al.*, 1990]. Based mainly on measurements in Rondônia and on data from the literature, *Steudler et al.* [1996] estimated that pasture grazing management in the Amazon released a net 2.4 Tg-CH_4 in 1990. To put this flux in perspective, we can compare it in terms of the 100 year global warming potential (GWP). The GWP of methane is 23 [*Prather et al.*, 2001, IPCC] so that a 2.4 Tg release of methane would be equivalent to 55 Tg CO_2 (~0.02 Pg-C). For nitrous oxide, the situation is reversed. Soils in undisturbed Amazon forests release copious amounts of nitrous oxide. Conversion of forest to pasture cuts nitrous oxide emissions by a factor of two to eight in the Amazon after a brief period of months to a few years of elevated emissions following forest to pasture conversion [*Verchot et al.*, 1999; *Melillo et al.*, 2001]. *Melillo et al.* [2001] extrapolated the results of their study and that of *Verchot et al.* [1999] to the scale of the Brazilian Amazon region using a simple cohort model for forest to pasture transitions and assigning fluxes to those transitions. For 1997, they estimated that conversion of forest to pasture resulted in a loss of 0.02 to 0.05 Tg N_2O-N. Conversion to CO_2-equivalent using a 100-year GWP of 296 [*Prather et al.*, 2001] yields the equivalent of a very small CO_2 sink from -9 to -23 Tg CO_2 (~0.00 to -0.01 Pg-C).

When *Houghton et al.* [2000] accounted for Amazon carbon fluxes resulting from land use change, they considered two potentially large terms that they could not quantify. These terms result from the release of carbon owing to selective logging and from forest fire. Both logging and forest fire remain poorly quantified in terms of the area exposed and the carbon lost from these effects.

In the Amazon region of Brazil, forests are rich in tree species but only a limited number of species are marketable for timber; therefore, loggers practice selective logging. Even though harvest intensities range from <1 to about 9 trees per hectare, logging can lead to substantial damage to the residual stands. Moderate harvests (~30 m^3 ha^{-1}) remove only about 11 Mg-C ha^{-1}. *Nepstad et al.* [1999a] estimated that logging during 1996–1997 affected between 10,000 and 15,000 km^2 y^{-1}. Most logging in the region is conducted by poorly trained workers with minimal planning. Waste and high levels of collateral damage are common [*Verissimo et al.*, 1992; *Johns et al.*, 1996; *Uhl et al.*, 1997; *Pereira et al.*, 2002]. The construction of logging infrastructure such as decks and logging roads is also an important source of mortality, damage, and ground and canopy disturbance [*Johns et al.*, 1996; *Uhl et al.*, 1997; *Pereira et al.*, 2002]. *Gerwing* [2002] found that intact forests contained about 17 Mg-C ha^{-1} of coarse woody debris (CWD) above 10 cm diameter. CWD increased to 34 Mg-C ha^{-1} at three "moderate intensity logging" sites that had 28 to 48 m^3 ha^{-1} of timber harvested using conventional logging (CL) sampled 4 to 6 years after harvest. These high levels of CWD production following logging suggest that logging could lead to a substantial loss of carbon stored in forests.

The carbon budget of logging in a forest depends upon the biomass harvested, the damage caused by the harvest, the decay of logging debris, and the rate of regrowth of the forest. Outside of the forest, the efficiency of production (proportion of finished product from timber harvested) and the decay of the finished products also affects the net carbon balance of logging. There are few data on any of these factors for the Brazilian Amazon and they have not been explored spatially. *Keller et al.* [in press] have attempted to model the carbon budget of logging from the Tapajos National Forest based on data on growth and debris formation taken from that site and similar sites. That study assumed only a single entry logging with a harvest of 30 m^3 ha^{-1} every 30 years consistent with good management practice. In reality, many forests suffer multiple entries as market conditions change. Therefore, estimates for this model are certainly conservative with regard to the carbon lost as a result of logging. In order to guess at the regional effects of logging, we have scaled the results from that study, assuming 30 years of harvest over an area of 15,000 km^2 y^{-1}. The results of our extrapolation are displayed in Table 1. Results are presented for CL and also for Reduced Impact Logging (RIL), which preserves a greater portion of the remaining stand. Rates of decay for coarse woody debris varying from 0.13 y^{-1} to 0.17 y^{-1} [*Chambers et al.*, 2000, 2001] have little effect on the outcome. The magnitude of this conservative estimate, nearly 0.03 Pg-C y^{-1} is substantial compared to net flux of clearing and regrowth that results in the release of ~0.2 Pg-C y^{-1} [*Houghton et al.*, 2000].

Table 1. Net ecosystem exchange from a model of logging effects in the Tapajos National Forest south of Santarem, Pará, scaled up to a logging scenario where 15,000 km^2 y^{-1} is logged over each of 30 years. The model accounts for logs removed from the forest, log processing, decay of finished products, decomposition of logging debris and forest regrowth following logging. Unlike most typical logging in the Brazilian Amazon, a single entry into the forest with a harvest of 30 m^3 of timber is assumed over the 30 year cutting cycle [Keller et al., in press]. Because of the assumptions, the carbon losses in these scenarios are likely to be conservative. The scenarios illustrated include conventional (CL) and reduced impact (RIL) logging. Instantaneous first order decay rates for decomposing debris are 0.13 y^{-1} (slow) and 0.17 y^{-1} (fast). 1 Tg = 10^{12} g.

Decay of Debris	Logging Technology	Carbon Lost in 30 y (Tg C)
Slow	CL	858
Fast	CL	874
Slow	RIL	552
Fast	RIL	551

The area of forest burned during each year is highly variable and depends on climatic conditions [c.f. *Langenfelds et al.*, 2002]. Forest fires are much more likely during drought years that are frequently associated with El Niño episodes such as occurred in 1997–1998. In a study in the Brazilian municipality of Paragominas, Pará, *Alencar et al.* [2004] found that 91% of all forest fires occurred during the three El Niño years (1983, 1987, 1992) in a ten year study period. Areas of fire occurrence are even less well known than those for logging. The effect of fire on regional carbon budgets is not well quantified. However, there are indications from global studies that the amount of carbon consumed by biomass burning is the single largest factor in the inter-annual change in the atmospheric carbon budgets [*Langenfelds et al.*, 2002; *van der Werf et al.*, 2004]. The largest inter-annual increases in the atmospheric carbon dioxide budget occurred during two periods over the interval 1992 to 1999. The years 1994/1995 correspond to times of high Boreal forest fire activity while the years 1997/1998 were El Niño years when large areas of tropical forest burned [*Siegert et al.*, 2001; *Mendonça et al.*, in press]. Fires in the Amazon probably contribute to these global effects, although forest fires that burned peat in Indonesia [*Page et al.*, 2002] may have been more important [*Langenfelds et al.*, 2002; *van der Werf et al.*, 2004].

On a local scale, forest fires have significant effects on forest carbon stocks. Forest fires in the Brazilian Amazon propagate mainly along the ground burning fine debris. While these fires release only a small amount of energy, they move slowly and cause high mortality in the thin barked, non-fire adapted forest vegetation. Two studies in eastern Pará compared biomass in forests that were previously selectively logged to forests that were first logged and later burned. In a study in the Tailândia municipality [*Cochrane and Schulze*, 1999; *Cochrane et al.*, 1999], logged but unburned forest contained about 121 Mg-C ha^{-1} of live biomass and 27 Mg-C ha^{-1}of necromass. Following one, two, and three burns respectively, the combined aboveground biomass and necromass was reduced to 135, 100, and 82 Mg-C ha^{-1} and the proportions of live biomass were 81%, 65%, and 29%. *Gerwing* [2002] compared "moderately logged" forests in Paragominas Municipality from which 4 to 6 trees ha^{-1} had been harvested 5 to 6 years prior to the study against forests with a similar logging history that had been burned between 1 to 6 years prior to survey. Burned forests were classified based on the total area contacted by fire as either "lightly" burned (1–2 burns) or "heavily" burned (2–3 burns). Logged forest contained about 161 Mg-C ha^{-1} of aboveground biomass plus necromass while lightly and heavily burned logged forests contained 140 and 89 Mg-C ha^{-1} respectively.

Tree mortality may not occur immediately following burning. *Barlow et al*. [2003] recently reported on plots surveyed one and three years following a ground fire in western Pará in the Reserva Extrativista Tapajós–Arapiuns. The plots were relatively undisturbed prior to the fire. The live biomass of undisturbed control plots was 190 Mg-C ha^{-1}. One year following burning, live biomass had declined by 23%. However, after three years, biomass had declined by 51%. Two-thirds of the biomass loss between the two measurements occurred in large trees (>50 cm diameter at 1.3 m above the ground). The total area of burned forest in the Amazon region is unknown; it is clear that were this area extensive, then burning of forest would lead to substantial emissions of carbon dioxide and other trace gases to the atmosphere.

THE ROLE OF FIRE IN LAND MANAGEMENT ACTIVITIES IN AMAZONIA

Fire is an important tool for land management. It is used by both large land-holders and smallholders alike. For smallholders, investments in machinery, herbicides and even fertilizers are out of reach; fire is the only practical tool that allows owners of small land holdings to clear forests and maintain growing crops or pasture. Fire not only clears debris following the slashing of vegetation, it also kills pests and converts the vegetation into nutrient-rich ash that both fertilizes the soil and neutralizes some of its acidity [*Nye and Greenland*, 1960]. Following fire, nutrient limitations, weed and pest invasions may limit cultivation to one to two years. But given sufficient time for secondary vegetation to recover between clearing burns (generally at low human population densities), this system known as swidden or slash and burn agriculture can be employed in rotation for centuries [*Palm et al*., 1996].

For large land-holders who concentrate on cattle raising, fire is also an economical means to initially clear forest and later to clear woody brush from pastures and to maintain pasture productivity and palatability. For initial land preparation, manual clearing and burning results in higher pasture productivity compared to mechanical land clearance [*Seubert et al*., 1977]. Pastures may remain economically productive through several burning cycles although eventually limitations in key nutrients (especially phosphorus) and the increased presence of herbaceous and woody invaders leads to degradation of pastures in the Amazon [*Dias-Filho et al*., 2001]. Long term pasture productivity requires fertilization and mechanization (tillage) for removal of woody perennial species. Potentially, high productivity pastures in the Amazon can be managed without fires [*Dias-Filho et al*., 2001].

Fire used for agricultural production often escapes its intended target, entering nearby forests, plantations, and fields as wildfire [*Nepstad et al*., 2001]. Previously logged forests are especially vulnerable to fire [*Uhl and Kaufmann*, 1990; *Uhl and Buschbacher*, 1985]. Forest fires increase the likelihood of future fires generating a positive feedback loop [*Cochrane et al*., 1999; *Nepstad et al*., 2001]. Once burned, tree mortality leads to canopy opening, a subsequent drying of the understory and an increase in the availability of fine fuels. These effects lead to greater flammability so that once burned, forests are more likely to burn a second time. No one has identified the length of time that previously burned forests remain more vulnerable to fire compared to undisturbed forests.

Understory forest fires in Amazonia are associated with human activities because people provide the main sources of ignition. In a regional analysis of satellite fire detection across the Brazilian Amazon, *Cardoso et al*. [2002] found that proximity to roads was the single most important factor for prediction of fires detected by satellite sensors. *Cochrane and Laurance* [2002] identified distance to forest edge as a key factor determining the probability of forest understory fire in the municipalities of Tailândia and Paragominas, Pará. *Alencar et al*. [2004] found that forest degradation (mainly through logging), forest fragment size, and distance to main roads or settlements, charcoal manufacture, and forest edges were all significant predictors of fire in a logistic regression model. *Sorrensen* [2000] studied fires by smallholders in the municipality of Santarém, Pará. She found that only 8% of the vegetation within a 55 m buffer bordering fires set by smallholders was logged or mature forest. The juxtaposition of flammable forests and fire dependent economic activities leads to a diversity of causes of forest fire across the region.

Even in agricultural areas, fires frequently burn out of control and cross property lines. Unintended burning can have severe economic consequences [*Nepstad et al.*, 2001; *Mendonça et al*., in press]. After burning, pastures must be rested for several months before they are grazed. Lost grazing opportunities cost money. Fires can destroy fence posts and other farm and ranch structures. When fire escapes into tree plantations or long-lived crops, complete losses may result following years of investment. The danger of fire discourages investment in perennial crops or tree plantations especially for small land holders who can neither insure against fire risk nor invest in adequate fire breaks. Fires that spread into forests potentially destroy valuable timber but the value of timber lost through accidental fire has not been quantified. The alternatives remaining for small holders are short-term slash and burn crops or extensive pasture development (Figure 1). Control of fire can foster investment by alleviation of risk.

Fire has economic effects beyond those associated with land management. Fires generate smoke particles and reactive compounds that have important atmospheric effects. Smoke and haze prevalent in the dry season in the southern and western Amazon leads to closure of airports. In 1996 and 1997 the airports of Rio Branco, Porto Velho, Imperatriz, Conceição de Aragaia, Carajás, and Marabá in 4 states of the Brazilian Amazon were forced to close for 420 hours because of smoke [*Nepstad et al*., 1999b]. Anecdotal information links road traffic accidents to smoky conditions.

Mendonça et al. [in press] have made an initial estimate of the economic costs of Amazon fire by examining the spatial and temporal relationship between respiratory ailments and fire occurrence, by estimating cattle ranching losses associated with fence damage and temporary loss of forage grass, and by examining timber losses and carbon emissions. During the severely dry year of 1998, losses to ranching and forestry, and costs associated with human health problems totaled approximately $50 million to $80 million. These losses could be overshadowed by the economic impacts of carbon released to the atmosphere through fire, which may have been as high as $9 billion in 1998, assuming that a ton of carbon emitted to the atmosphere exerts $20 worth of damage on the world economy [*Mendonça et al.* in press]. The uncertainties surrounding these estimates are large, because of a shortage of information about the area of forest that is burned each year and the effects of fire on forest carbon and timber stocks. It is clear, however, that the economic costs of fire are high, perhaps reaching a few percentage points of the Amazon region's gross domestic product.

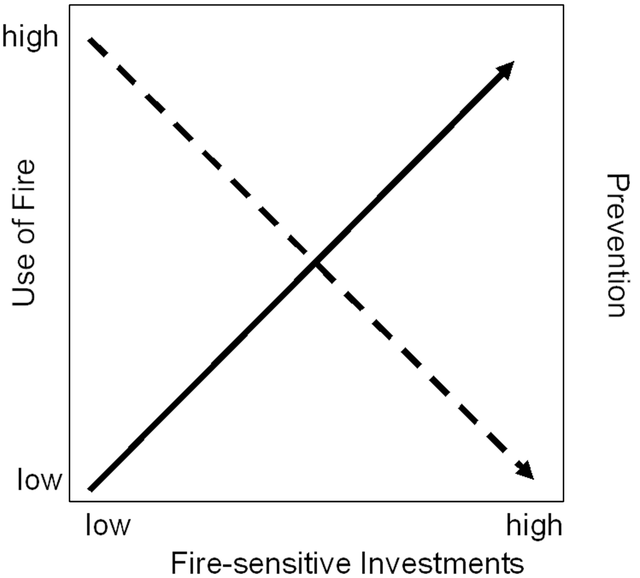

Figure 1. The relation between use of fire, fire prevention efforts, and fire-sensitive investments. Greater investment in intensive (fire-sensitive) land uses are accompanied by greater fire prevention efforts and less use of fire.

EFFECTS OF SMOKE ON ATMOSPHERIC PROCESSES

Extensive fires occur during the dry season throughout the tropics and sub-tropics. In Brazil, they are most prevalent in the *cerrado*. However they are also very common in the so-called "arc of deforestation" that follows the eastern and southern boundaries of the forested zone in the Brazilian Amazon in the states of Pará and Mato Grosso [*Cardoso et al*., 2002]. The smoke from these fires has local effects and it is also transported long distances where it contributes to air pollution in South and Southeast Brazil and perhaps even in neighboring countries (Plate 1) [*Longo et al*., 1999; *Freitas et al*., 2004].

Smoke from biomass fires has both direct and indirect effects on the radiative properties of the atmosphere. Smoke aerosols directly can both absorb and scatter incoming solar radiation and radiation emitted from the land surface. Smoke contains a considerable concentration of black carbon and organic materials that are dark and absorptive. During peak period of biomass burning during August–September 1999 at Alta Floresta in Mato Grosso state and Fazenda Nossa Senhora, near Ji-Paraná, Rondônia, in the arc of deforestation, *Schafer et al.* [2002] measured reductions in the expected total solar radiation reaching the surface of 30 to 50%. The net effect of this absorbing aerosol is to warm the atmosphere and cool the surface [*Guyon et al*., 2003] leading toward greater stability and reduced convection in the atmospheric boundary layer. This results in a reduction of trade wind cumulus clouds over large areas of the Amazon during the smoky season [*Koren et al.*, 2004]. The effect of aerosols in clouds which include the ice phase is still uncertain; models indicate a highly non-linear dependence on environmental variables such as moisture and wind fields [*Khain and Rosenfeld*, 2003].

Smoke also contributes to indirect effects on the atmospheric radiative balance. There are two indirect effects [*Ramanathan et al*., 2001]. The first of these indirect effects is to increase the number (and decrease the size) of droplets in clouds. Increased droplet numbers make clouds more reflective, leading to climatic cooling. Assuming a constant amount of cloud water, under smoky conditions, the droplets will be

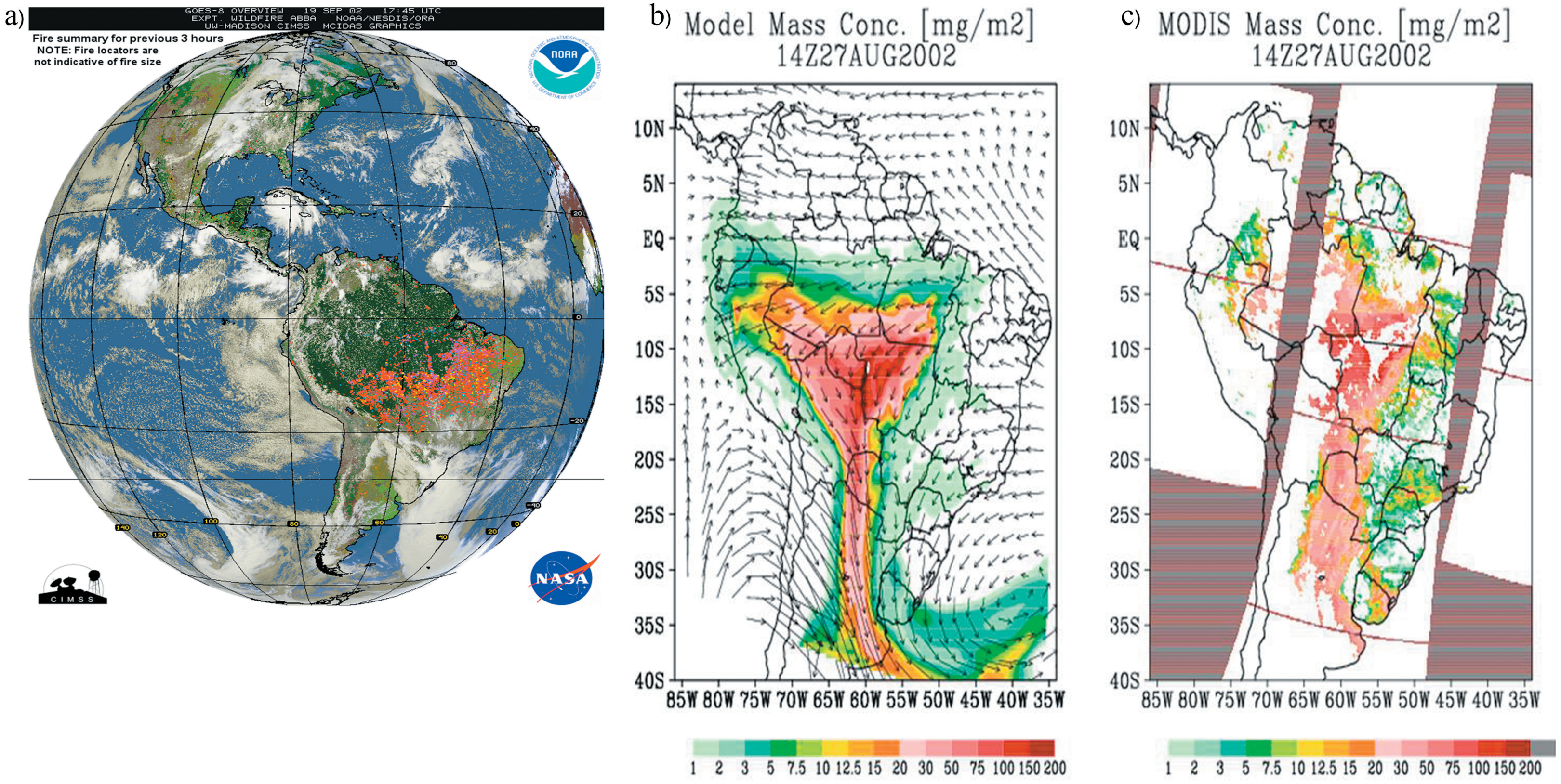

Plate 1. Fires in the savanna and forest regions of the Amazon are evident along the southern and eastern boundaries of the Amazon basin in the NOAA GOES satellite image processed to show fire hotspots (a) [*Prins et al.*, 1998]. Particulates produced by fires (estimated by hot spots) are injected into atmospheric transport models (b) that clearly show the long-distance effects of fire. In this model case, confirmed by retrievals of MODIS data from NASA's Terra satellite (c), a "river of smoke" is exported over Southern Brazil, Uruguay, and Argentina [*Freitas et al.*, 2004].

smaller. Small droplet size suppresses rain formation by coalescence and thereby increases cloud lifetime in stratus and small cumulus clouds to further increase the reflection of solar radiation to space. This is the second indirect effect.

The reduction of cloud droplet size over the Amazon during the biomass burning season has been observed by satellite [*Kaufman and Fraser*, 1997]. In addition, the suppression of precipitation by smoky clouds has been observed in satellite measurements by *Rosenfeld* [1999] over Indonesia. Recently, these satellite observations have been confirmed by *in situ* measurements over the Amazon during the LBA–SMOCC (Smoke, Aerosols, Clouds, Rainfall, and Climate) campaign in September to November 2002 [*Andreae et al.*, 2004]. During this campaign, a set of flights with two aircraft measuring warm cloud physical properties and atmospheric chemical properties were flown along a transect over the southern Amazon. They extended from smoke-polluted regions over the Brazilian states of Rondônia and Mato Grosso to adjacent clean regions in the Brazilian states of Acre and Amazonas with similar airmass thermodynamic properties. Clouds over the clean undisturbed forest region had a broad distribution of cloud droplet sizes and warm rainfall was observed on aircraft radar and on the aircraft windshield at approximately 1500 m above cloud base (1200 to 1500 m altitude). In contrast, the modal drop size in smoky clouds and in clouds generated over fires (pyro-clouds) was smaller, the droplet size distribution was narrow (only small droplets) and no rain was observed to the limits of the aircraft operational altitude, approximately 4000 m. Based on estimation from satellite retrievals, the height to precipitation in smoky cumulonimbus clouds sampled during LBA–SMOCC was about 6700 m above a cloud base of 1700 m [*Andreae et al*., 2004].

Vigorous convection and violent hail storms were observed in the smoky regions during the SMOCC campaign. Potentially, the effect of smoke aerosols to shift the precipitation regime from warm rain to ice precipitation can have repercussions for global climate. Ice precipitation releases more latent heat and does so at higher altitudes where it affects the propagation of planetary scale waves that provide inter-hemispheric teleconnections [*Kasahara and Dias*, 1986; *Grimm and Dias*, 1995].

Finally, it has been suggested that biomass burning smoke has even been partly responsible for the doubling of stratospheric water vapor over the past half century [*Sherwood*, 2002]. The essence of the argument is that biomass burning derived aerosols in towering tropical cumulonimbus clouds lead to a reduction in ice crystal size and that small ice crystals are more likely to be lofted to the stratosphere. Half of the global increase in stratospheric moisture content can be accounted for by the increase in atmospheric methane concentration. How much of the other half is accounted for by this biomass burning related mechanism remains an open question.

FIRE AND FUTURE DEVELOPMENT: A CRITICAL JUNCTURE

As we have shown in this paper, our understanding of ecosystem–climate–chemistry interactions in the Amazon is increasing rapidly. Amazonia is reaching a new critical juncture in its development as agriculture intensifies in some regions. In the past few years, the spread of soybean and grain cultivation has moved from the Brazilian *cerrado* into forested regions of the Amazon. While there is no certainty that soybeans and other row crops (referred to hereafter as grains) grown on large mechanized farms will have long-term success in the forested regions of the Amazon, the expansion of this agricultural practice fostered by Brazilian and multi-national business interests raises some interesting questions about the future of Amazon development. Grain producers in forested regions are currently expanding their agriculture on lands that had previously been cleared and were covered by pastures or secondary growth. Preparing old growth forest lands for mechanized agriculture is far more expensive than land preparation in the previously cleared areas because of the costs of removal of large trees and tree stumps, although part of that cost might be offset by products such as timber and charcoal.

Mechanization has an important benefit. While fire is used in the preparation of fields for mechanized grain agriculture, it is not part of the normal management schedule for soybeans, rice and corn. Mechanized agriculture lowers the production of smoke and furthermore reduces the risk of wildfire in its vicinity.

Because grains are being produced on already cleared lands, currently grain production does not appear to lead directly to deforestation of old growth forests. However, in regions where grain production has expanded, the price of flat cleared land amenable to mechanized agriculture has increased enormously (*C. Steward and D. Nepstad*, unpublished data). Clearing of forested areas suitable for mechanized agriculture may increase simply as a result of speculation. In addition, ranchers and smallholders who sold their land to grain farmers may wish to continue their former activities in new areas. The movement of these land managers to new areas would potentially lead to an increase in the rate of deforestation.

The shift to large scale mechanized grain agriculture as a new mode of production on the forest frontier puts the development pathway at a critical juncture. Will development of mechanized agriculture simply accelerate the pace of all land use change? This is the common path that most frontier areas have followed. Alternatively, can the wealth generated by this lucrative form of management be used as a subsidy for inten-

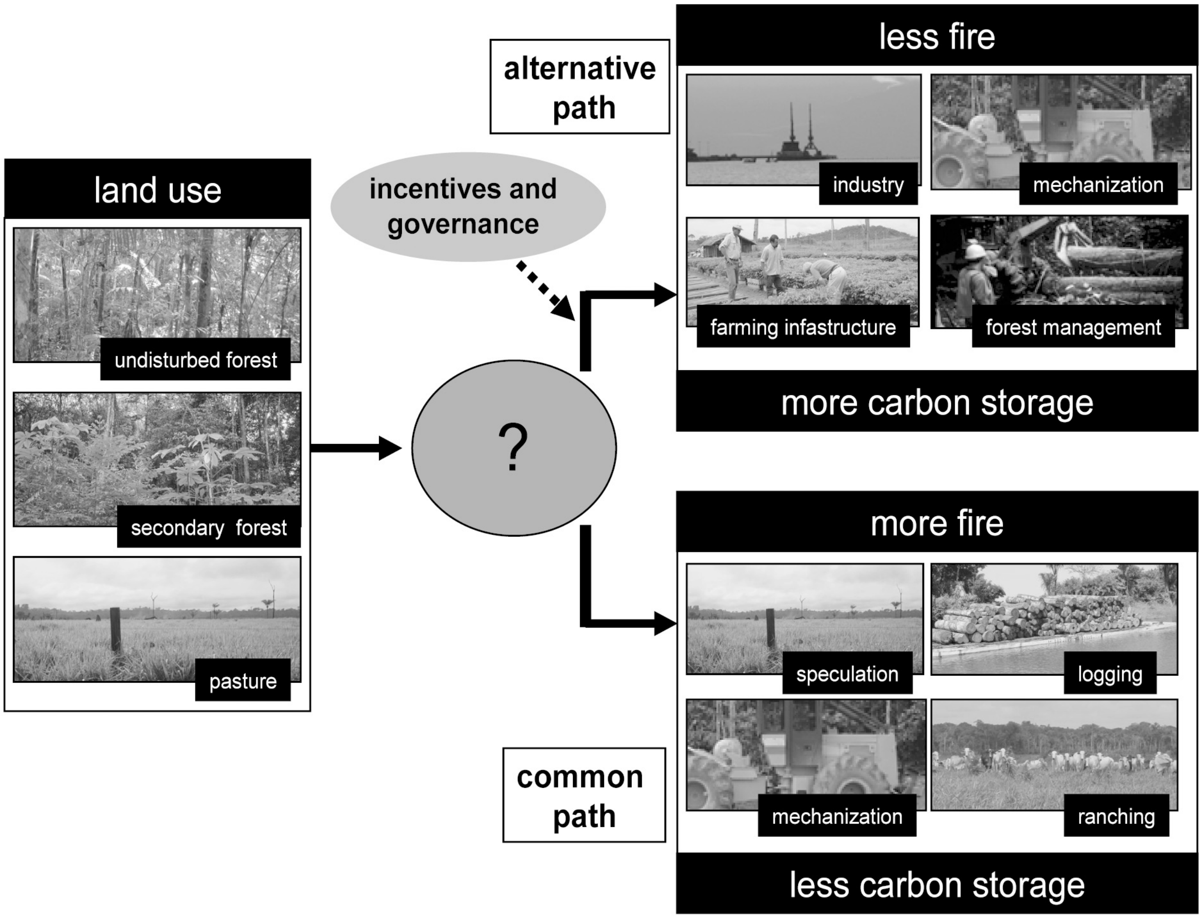

Figure 2. On a local scale, intensive mechanized grain agriculture leads to a reduction in the use of fire. However, the wealth generated from intensive agriculture may be reinvested in traditional extensive land uses that promote fire. The question of whether Amazonia will follow this common path generating more fire or an alternative path with less fire depends upon government policy. Incentives can encourage intensive development of farming infrastructure, managed forestry, and industry to guide development onto an alternate path.

sification of development in limited regions? Other less suitable regions could be devoted to forest management and other forms of management that allow for greater conservation of biological diversity and ecosystem services such as increased carbon storage and the maintenance of climate. We label this the alternative path (Figure 2).

Following the common path, wealth generated by the sale of newly appreciated lands will end up reinvested in land speculation and land clearance for new farms and ranches or invested for other ventures in the forest regions such as commercial logging. The wealth generated by land sales to grain producers and the profits of the grain producers themselves may generate indirect effects. Grain producers, acting either politically to influence government policy or through direct investment, desire to improve transportation infrastructure, roads and waterways, to move their product to market. The same transportation corridors that are used to transport grain will reduce the price of transport for logs, cattle, and farm produce grown by smallholders. If history is any guide, the economic benefits of any new road construction or paving will lead to a new pulse of forest clearance [*Nepstad et al.*, 2001; *Alves et al.*, 2002]. Without large investments in regional development planning, land tenure, and enforcement, the wealth generated from the expansion of mechanized grain agriculture will hurry Amazonia along the common path [*Nepstad et al.*, 2002].

Incentives to follow an alternative pathway to development must redirect wealth into intensive land use within the grain growing regions, into sustainable alternative forestry outside of the intensive regions, or into industrial development in the cities. Where industry is fomented, as in the case of Manaus, population leaves the countryside for the city. Deforestation in the vicinity of Manaus is very limited compared to the surroundings of much smaller towns in Pará, Rondônia, or Mato Grosso. The alternative path has few historical antecedents. Can Brazil and other Amazonian countries find a new way? Unfortunately, the common path suggests a poor prognosis for the future health of the Amazon ecosystem.

The current challenge for researchers in Amazonia is to use our expanded knowledge of the functions of the Amazon ecosystem combined with growing understanding of the social and economic dimensions of the settlement of the forest frontier. Taken together, this knowledge and understanding may provide policy makers with indications of where to apply leverage in order to direct development along a sustainable pathway.

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