The Spatial Distribution and Interannual Variability of Fire in Amazonia

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Charcoal evidence suggests that fires in Amazonian forests were an infrequent agent of forest disturbance prior to the twentieth century. However, the spatial and temporal distribution of fires changed dramatically during the past few decades. Fire has become one of the driving forces of land use and land cover change in Amazonia. Increasing human intervention in the region, in conjunction with climate anomalies, has exposed tropical forests to an unprecedented amount of vegetation fires with important consequences to the functioning of the complex Amazonian system and atmospheric concentrations of greenhouse gases. In this chapter, the main fire types in Amazonia are discussed: deforestation, maintenance, accidental, and natural fires. The major causes and consequences of vegetation fires are analyzed in light of their social, economic, and biophysical drivers. Satellite data are used to derive current maps describing the spatial and temporal distribution of fires in the region, highlighting some of the important linkages between human activities and climate conditions that combine to create unique anthropogenic fire regimes across Amazonia.

1. INTRODUCTION

Amazonian forests have long been disturbed by fires [*Meggers*, 1994]. Geological data provide evidence of charcoal deposits in soils of mature forests in the Amazon basin indicating historical, however infrequent, fire activity in the region [*Sanford et al*., 1985; *Meggers*, 1994]. The low historical fire frequency is largely explained by the high humidity and rainfall levels that characterize the region and which often prevent natural fires from developing [*Goldammer*, 1990; *Ray et al*., 2005; *Uhl and Kaufmann*, 1990]. However, since prehistorical times, humans have learned to manipulate fire and use it as a major hunting weapon and agricultural tool [*Goudsblom*, 1992]. The more recent history of fire occurrence in Amazonia is marked by a contrast between low frequency natural fires and the growing dominance of anthropogenic fires as human occupation in the region has increased.

In the past few decades, droughts related to El Niño–Southern Oscillation (ENSO) episodes, combined with the encroachment of human settlements in the region and the development of transportation infrastructure have transformed fire into a major environmental threat to the Amazonian ecosystem and regional climate [*Cochrane et al*., 1999; *Nepstad et al*., 1999a; *Alencar et al*., 2004]. In the past, intensity and frequency of fires were not severe enough to change the ecosystem, but nowadays, humans have transformed fire into a chronic, persistent element of the local landscape. In the Brazilian part of Amazonia alone, fire is currently the primary land clearing and management approach for an estimated four million farmers [*Nepstad et al*., 1999b]. The occurrence of major destructive fire seasons is no longer constrained to

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ENSO years and, combined with climate change, may accelerate the conversion of the rainforest into savanna-like vegetation [*Nepstad et al*., 2004].

Vegetation fires in Amazonia have been monitored routinely since the mid-1980s with the use of satellites [*Setzer and Pereira*, 1991]. Satellite data are particularly useful for monitoring fires in Amazonia as they provide systematic information on fire activity for the entire region, including the most remote areas where ground-based observations are difficult. The number of operating satellite systems with fire monitoring capabilities has significantly increased in the past decade, thereby augmenting our capacity to delineate the spatial and temporal patterns of fire distribution in the region.

In this chapter, we describe the spatial and temporal distribution of vegetation fires with a focus on Brazilian Amazonia. We start with a discussion of the fundamental causes (section 1) and consequences (section 2) associated with the use of fire to promote land use and land cover change. In section 3, we present a brief overview of the main satellite systems and products which are available to monitor and evaluate fire activity in the region in order to (in sections 4 and 5) explore the spatial and temporal distributions of fire detections which can be derived using those products.

2. VEGETATION FIRES IN AMAZONIA: MAJOR CAUSES

Vegetation fires vary according to cause, intensity, duration, and spatial pattern. In order to properly address the subject, it becomes necessary to draw a distinction between the different types of fire based on their physical properties, while incorporating the aspects and the implications of the policies designed to control them [*Alencar et al*., 1997; *Nepstad et al*., 1999b]. Fires in Amazonia can be classified into four major groups:

Q2 1. "Deforestation fires": These are intentional fires used to facilitate land clearing for forest conversion into crop production or pasture in the initial stages of frontier occupation and deforestation [*Nepstad et al*., 1999b]. Typically, forests are cut down in the first months of the dry season, and the slashed biomass is left to dry under the sun for 2 to 3 months, depending on the biomass volume, initial moisture content, and weather conditions [*Sorrensen*, 2004]. Fire is used as a cost effective technology to provide rapid transformation of the dried organic matter into short-lived fertilizing ash. This method is utilized in the deforestation process by small subsistence farmers, as well as by large-scale mechanized agriculture and cattle ranchers alike. The same process is used to convert young and advanced succession forests, locally known as "Capoeiras," in the shifting cultivation process used by an estimated half million small agricultural households in Brazilian Amazonia [*Sorrensen*, 2004]. A survey conducted in five regions along the Arc of Deforestation between 1995 and 1996 suggested that approximately 13% of the area burned was due to deforestation fires [*Alencar et al*., 1997; *Nepstad et al*., 1999b]. The total annual deforested area estimated for Brazilian Legal Amazonia by the PRODES project in the same period peaked at 29,000 km^2. Deforestation rates averaged approximately 22,000 $km^2\ a^{-1}$ from 2000 to 2005 [INPE, 2005].

2. "Maintenance fires": These are also intentional fires used in the management of pastures as well as for clearing crop residue. Pastures in Amazonia, particularly those recently established, are frequently invaded by pests, weeds, and other competing natural vegetation. Moreover, within a few years of planting, pastures lose vigor as soil fertility declines [*Uhl and Buschbacher*, 1985] (Declines in pasture Q3 productivity vary tremendously from a few years to more than a decade depending on the cattle stocking rate, grass species, and management practices such as rotation and control of erosion and leaching, etc.). Cattle also prefer newer, tender sprouts as opposed to old unpalatable grasses. Hence, fire is used as an inexpensive means to control weeds, to restore part of the soil fertility, and to rejuvenate grasses. Unlike deforestation fires, maintenance fires are rapid and low in intensity due to the reduced amount of biomass fuel. It is suggested that this type of fire affected an area of 20% of the total area burned along the Arc of Deforestation during 1995–1996 [*Alencar et al*., 1997; *Nepstad et al*., 1999b].

3. "Accidental fires": These are fires that escape control from intentional burning associated with nearby maintenance or conversion fires. Accidental fires are known to affect forest areas as well as rural properties in already deforested zones. In the case when forests are accidentally burned, the problem will normally be concentrated along forest edges in areas of active deforestation and land use [*Nepstad et al*., 1999b; *Gascon et al*., 2000; *Cochrane and Laurance*, 2002]. Nevertheless, this type of fire may impact large regions during exceptionally dry years when fire lines can penetrate the forests and affect areas far away from their ignition sources [*Elvidge et al*., 2001; *Nelson*, 2004]. Charcoal pits are an- Q4 other important ignition source of accidental fires, especially in Eastern Amazonia [*Alencar et al*., 2004]. Fires which accidentally burn forests will possess different characteristics depending on the degree of alteration of the affected areas. In relatively intact forests, fires are low in intensity, move very slowly, and tend not to spread to large areas [*Cochrane and Schulze*, 1998; *Cochrane*, 2003]. On the other hand, forests disturbed by logging or previous fires are much more prone to subsequent, long-lasting, intense fires that can burn extensive areas [*Nepstad et al*., 1999a]. Fragmented forests

are more susceptible to fires because of the larger amount of available dry matter and canopy openness to air currents and winds which help feed the fire lines [*Cochrane and Schulze*, 1999; *Cochrane*, 2003; *Alencar et al*., 2004]. The expansion of economic activities and the increasing intensity and frequency of ENSO events may promote a future of more frequent and larger forest fires in the region [*Nepstad et al*., 1999a]. *Alencar et al*. [2006] suggest that forest fires during ENSO years can burn an area two times larger than that resulting from deforestation. Accidental fires affecting rural properties in already deforested areas can also cause significant damage to crops, plantations, pastures, and infrastructure, resulting in great economic losses [*Alencar et al*., 1997; *Mendonça et al*., 2004]. According to a survey performed over five study sites along the Arc of Deforestation in 1996 [*Nepstad et al*., 1999b], those types of escaped fires were responsible for 47% of the area burned in that period, which represented an average rainfall year.

4. "Natural fires": Natural fires are those caused by lightning strikes (Other natural causes include friction fires sparked by falling rocks, and landslides, volcanic fires, and prism fires caused by the sun's light beams deflected by crystal rocks [*Stott*, 2000]. Those types of fires are much rarer than lightning fires and, to our knowledge, no case has ever been documented in Amazonia.). Although lightning strikes along the intertropical convergence zone (ITCZ) are very common [*Stott*, 2000], quantification of natural fire events in Amazonia is difficult due to limited data. Anecdotal reports suggest, however, that natural fires are rather infrequent in the region as lightning is often accompanied by rain, which extinguishes the initial ignition and prevents flame propagation [*Ramos-Neto and Pivello*, 2000; *Stott*, 2000]. (The litter material must also be dry and arranged properly to burn. Moreover, not all striking episodes have high amperage and low voltage necessary to convert the electrical charge into fire. In some cases, the lightning strike will be "cold" and
Q5 blast without producing fire [*Pyne*, 2001].). In fact, the vast majority of fire events in Amazonia are caused by intentional or unintentional human action and very few can be attributed to natural causes [*Goldammer*, 1990].

Fire events detected by satellites are spatially concentrated on or near deforested fields [*Cochrane*, 2001; *Cochrane and Laurance*, 2002; *Alencar et al*., 2004, 2006]. The different types of fires described above may be influenced by social, economic, and political factors, as well as by biophysical conditions, resulting in distinct spatial and temporal patterns of fire activity across the region (see maps and description in sections 3–5 below). For instance, *Alencar et al*. [2004] found that accidental forest understory fires during ENSO and non-ENSO years are strongly correlated with distance to main roads, charcoal pits, and settlements. *Arima et al*. [2007] showed that the probability of fire is positively correlated with the farmgate price of beef and soybean, even when controlled for the amount of rainfall and different soil types. Higher farmgate prices provide an economic incentive for the conversion of forests into agricultural land and consequently to the use of fire as a management tool.

Cultural factors also help explain why certain areas are more fire prone than others. *Simmons et al*. [2004] suggested that the cohesiveness and identity of communities can influence the likelihood of accidental fires. *Moran et al*. [2006] suggest that communities that practice slash and burn agriculture have their own ways to cope with fire, particularly during ENSO years. Thus, more traditional communities tend to use their empirical knowledge to prevent escaped fires, in contrast to newly formed ones. However, the uncontrolled fires ignited by humans during 2005 in Acre, which affected an area of approximately 300,000 ha of forests, indicate that an intense drought can foster fire tragedies anywhere in Amazonia.

In terms of institutional factors, *Arima et al*. [2007] estimated that areas protected by the federal government, such as indigenous lands and conservation areas, reduced the probability of fire by 33% on average, keeping rainfall, and distance to deforestation and infrastructure constant. *Nepstad et al*. [2006a] showed that even inhabited reserves such as indigenous lands and extractive reserves successfully prevent fire. On average, fire occurrence outside those areas was four times higher (see also *Bruner et al*. [2001] for a discussion of the effectiveness of protected areas in tropical regions).

Biophysical factors, particularly rainfall levels and water holding capacity of soils, also affect the likelihood of fires [*Nepstad et al*., 2004]. *Arima et al*. [2007] showed that the probability of fire in Brazilian Amazonia decreased on average from 10% to virtually zero when rainfall increased from 1400 to 3000 mm a^{-1} even controlling for distances to deforested areas and to infrastructure. Soil water holding capacity is also critical to fires particularly during severe droughts in El Niño years. For instance, *Nepstad et al*. [2001] estimated that nearly 1 million km^2 of forests had become vulnerable to fire during the 1997–1998 El Niño because the available soil water to plants was depleted up to 10 m in depth. The deep roots of Amazonian forests are giant pumps that extract water from the soil up to 18 m deep maintaining a humid forest understory during the 3- to 4-month dry season [*Nepstad et al*., 1994], thereby reducing the probability of fire spread.

3. CONSEQUENCES OF VEGETATION FIRES IN THE AMAZONIA

Fire has been one of the most important agents of landscape transformation in Amazonia. In rural Amazonia, fire assures initial productivity of the recently deforested areas in the absence of technological alternatives and soil correction [*Sorrensen*, 2004]. In addition, fire is also the most affordable and reliable management tool used to control weeds, favoring grass species used for cattle grazing. Despite the important role of anthropogenic fire in the Amazonian production system, its intensive and uncontrolled use can have major consequences to the region's ecosystem as well as to its people. These consequences include impacts on ecological and biophysical processes, regional and local economies, and impacts on health and societal behavior.

3.1. Ecological and Biophysical Consequences

Fires can affect ecological and biophysical processes at different scales. At a local or stand scale, the ecological consequences of uncontrolled and more frequent fires in tropical forests include, but are not limited to (1) increased vulnerability of forests to recurrent fires [*Nepstad et al*., 1995; *Cochrane and Schulze*, 1999]; (2) changes in biodiversity including large-scale tree mortality [*Barlow et al*., 2003; *Holdsworth and Uhl*, 1997; *Barbosa and Fearnside*, 1999; *Cochrane and Schulze*, 1999; *Gerwing*, 2002; *Haugaasen et al*., 2003], changes in forest composition and fruit availability, and impacts on faunal populations [*Barlow et al*., 2002; *Barlow and Peres*, 2004a, 2006; *Peres et al*., 2003]; (3) changes to soil nutrient availability influencing vegetation recovery in areas of secondary forest regrowth [*Buschbacher et al*., 1988; *Hughes et al*., 2000; *Moran et al*., 2000; *Zarin et al*., 2005]. Although fires occur at the landscape scale, the increase of fire activity in Amazonia can have major consequences to the regional and global climate as well [*Nobre et al*., 1991; *Rosenfeld*, 1999; *Andreae et al*., 2004; *Artaxo et al*., 2005].

In terms of local impacts, forest fires promote significant changes in forest structure. Several studies have reported considerable reduction in aboveground biomass of forests disturbed by logging and fire. In these forests, a single fire can kill from 15% to 50% of the standing trees [*Holdsworth and Uhl*, 1997; *Barbosa and Fearnside*, 1999; *Cochrane and Schulze*, 1999; *Gerwing*, 2002; *Haugaasen et al*., 2003], thereby reducing the canopy closure through leaf shedding. The decrease of the leaf area index favors the increase of incoming solar radiation, drying the forest interior and increasing the amount of dead material and the forest floor fuel layer [*Uhl and Buschbacher*, 1985; *Uhl and Kauffman*, 1990; *Nepstad et al*., 2001; *Ray et al*., 2005]. In general terms, when an understory fire kills trees, it perpetuates the formation of gaps and fuel material on the forest floor in subsequent years [*Nepstad et al*., 1995, 2001; *Cochrane and Schulze*, 1999]. These effects on forest structure are also reproduced by logging operations, which are recognized as one of the main anthropogenic disturbances contributing to forest flammability [*Holdsworth and Uhl*, 1997; *Cochrane et al*., 1999]. This interaction between logging and fire creates a positive feedback, which enhances the forest flammability following the initial disturbance [*Nepstad et al*., 2001; *Cochrane*, 2003].

Fire is an important disturbance influencing the rate and pattern of ecological succession of tropical forests [*Goldammer*, 1990; *Chazdon*, 2003]. Forest regeneration in Amazonia is a slow process which can span several decades [*Steininger*, 1996; *Tucker et al*., 1998; *Zarin et al*., 2005]. Exposure to subsequent fires can compromise the reestablishment of less resistant plant species and lead to changes in forest composition [*Uhl et al*., 1988; *Uhl and Kauffman*, 1990]. Recurrent fires can retard succession to a point where it becomes difficult to reestablish the natural recovery process [*Goldammer*, 1990; *Chazdon*, 2003]. In addition, consecutive fires affecting areas of forest regrowth will negatively impact the nutrient elemental pools [*Hughes et al*., 2000; *Zarin et al*., 2005], limiting the forest capacity to recover.

Changes in forest structure and composition due to fire will also affect biodiversity [*Laurance*, 2003]. *Barlow et al*. [2002] found that several types of avifauna were negatively impacted by the large scale 1997–1998 ENSO forest fire that occurred in Tapajós/Arapiuns Extractive Reserve, in the low Amazon region. These fire disturbances reduced the abundance of invertebrate communities, decreasing the availability of prey density to some bird species [*Haugaasen et al*., 2003]. Moreover, the heat produced by surface fires stresses trees, reducing the food supply to vertebrate frugivores and causing a decrease of these populations in recently burned areas [*Barlow and Peres*, 2006; *Peres et al*., 2003]. However, few studies have addressed the long-term response of biodiversity to fire in the region. A study conducted in eastern Amazonia indicated that game vertebrates (e.g., tapir, deer, agouti) tend to return to previously burned areas, since they now have new source of foraging substrate (regrowing vegetation), and they are protected by the dense understory vegetation established years after the fire, making it difficult for hunters to access these areas [*Carvalho and Nepstad*, 2000]. *Barlow and Peres* [2004b, 2006] also reported continued tree mortality and changing population dynamics among vertebrates when analyzing areas affected by fires 3 years after the initial burning event.

Large-scale forest fires and the increase of fire activity, as a whole, in Amazonia also affect the regional and global climate systems. Climatic consequences of fires are mainly observed through an increase in both direct and committed CO_2 emissions [*Barlow and Peres*, 2004a; *Barbosa and Fearnside*, 1999; *Alencar et al*., 2006], as well as the emissions of methane and other gases and substances [*Fearnside*, 1997; *Potter et al*., 2002; *Davidson and Artaxo*, 2004] and through changes in surface properties (e.g., albedo, evapotranspiration, sensible and latent heat fluxes). While biomass burning emissions have an important role associated with the processes that control radiation balance and cloud formation [*Penner et al*., 1992; *Andreae et al*., 2004; *Koren et al*., 2004], surface cover change through forest fragmentation is recognized by major climate models as a key element which could lead to the savannization of large areas and to an increase in the risk of wildfires [*Hoffmann et al*., 2003a; *Betts et al*., 2004; *Cox et al*., 2004; *Cowling and Shin*, 2006].

The increase of biomass burning emissions affects the incoming solar radiation in Amazonia (e.g., increase in diffuse radiation) [*Nemani et al*., 2003], and this tendency may alter forest structure by favoring particular species of the plant community (e.g., increasing liana density). In addition, physiological and biogeochemical processes in old-growth tropical forests can be influenced by changes in atmospheric composition and land surface dynamics which include (1) rising atmospheric CO_2 concentration, (2) an increase in land surface temperature, (3) changes in precipitation and ecosystem water availability, and (4) changes in disturbance frequency [*Chambers and Silver*, 2004]. Process-based ecosystem models used to simulate the impact of fire in promoting future changes in climatic patterns showed large declines in net primary productivity and release of carbon as a result of Amazonian forest dieback [*Friend et al*., 1997]. The negative impacts of fires and biomass burning emissions can be exacerbated by ENSO events, which promote severe droughts in the region [*Van der Werf et al*., 2004]. These effects of climate change constitute a positive feedback in which the degraded forests become less effective at sequestering carbon and regulating regional climate, while becoming more susceptible to fire [*Nepstad et al*., 2001].

In sum, fire impacts climate which is a major determinant of the biological activities of plants, including phenology, physiology, distribution, and plant-animal interactions [*Wright*, 2005]. If the trend of more extreme droughts and increased fire activity in tropical moist forest continues, it may result in replacement of tropical moist forest species with more drought-tolerant and fire-resistant forms of scrubby, open vegetation resembling the cerrado (scrub savanna) of central Brazil [*Shukla et al*., 1990].

3.2. Economic Consequences

There are several economic losses associated with vegetation fires. The most common results from the direct impacts associated with fires that escape control are, namely, the loss of cattle and crops, and damages to infrastructure. However, other economic consequences include basin-wide effects associated with airport closures due to smoke and power outages due to fires along power lines. In addition, forest fires contribute to reducing forest value to society while influencing investments in rural areas.

Forest fires decrease the production and cause mortality of important nontimber forest product species such as fruit and medicine trees and vines [*Peres et al*. 2003; *Shanley and Medina*, 2005]. *Peres et al*. [2003] reported losses of fruit trees due to forest fires along the Rio Tapajós with implications to game frugivore vertebrates. *Shanley and Medina* [2005] reported a decrease of about 80% in the family consumption of economically important fruit trees after a forest fire.

The use of fire is the main characteristic of the Amazonian agriculture frontier, where land use investments are low, and the risk of accidental fire is high [*Nepstad et al*., 1999b, 2001; *Sorrensen*, 2004]. Every year, accidental or escaped fires from agriculture and pasture fields cause major economic losses in the region. Fire affects small- and large-scale farmers and ranchers by burning infrastructure such as fences, buildings, and equipment, leading to reduced production capacity [*Alencar et al*., 1997; *Nepstad et al*., 1999b; *Mendonça et al*., 2004]. Other consequences include losses of crop fields, pasture, and cattle. The risk of such losses end up influencing land use type and management decisions, perpetuating land use practices that use fire and discouraging investment in more sustainable methods [*Nepstad et al*., 2001]. In this scenario of high fire risk, extensive cattle ranching and annual crops are preferable if compared to more vulnerable and intensive land uses such as perennial crops [*Walker et al*., 2000]. In summary, investment in more sustainable land management is likely to decline as fire risk increases [*Nepstad et al*., 2001].

The consequences of escaped fires affect more than nonforest land uses. Forest fires were estimated to represent a loss of approximately US$5 per hectare in terms of marketable adult trees in the Paragominas region [*Mendonça et al*., 2004]. In that region alone, one of the most important logging centers in Amazonia, this monetary loss was estimated at more than US$13 million during the ENSO 1997–1998 period [*Mendonça et al*., 2004]. In other areas where the economic loss per hectare of forest can be higher, forest management becomes even more risky. The high rates of tree mortality promoted by forest fires discourage more sustainable forest management practices such as reduced impact logging [*Nepstad et al*., 2001]. The chance of losing the second and third harvest cycles due to uncontrolled fires is one of the several factors that contribute to more intensive harvest operations. This logging pattern also increases the likelihood of fire spread creating a positive feedback between logging practices and forest fire risk [*Nepstad et al*., 2001].

The smoke from fires also can reduce the visibility leading to airport closures and cause shortcuts in power lines interrupting energy transmission [*Mendonça et al*., 2004]. Despite the apparent importance of this type of economic loss, these consequences of fire to the regional economy are still to be estimated. However, it is possible that a future of more intensive fire activity in Amazonia can increase the awareness of this type of economic loss and push for quantification and investment on more effective public policies to control fire.

3.3. Social Consequences

Increased incidence of smoke-induced respiratory illnesses is normally observed at the peak of fire seasons [*Mendonça et al*., 2004]. School closures are also reported during days of extreme smoke concentration, for example, in Acre in 2005. Along with the direct impacts to human health, forest impoverishment due to fires can lead to reduced productivity, thereby influencing patterns of land abandonment and poverty.

Smoke-induced respiratory illness is responsible for an average of 9000 in-patients every year during the burning season in Amazonia [*Mendonça et al*., 2004]. In fact, fire can affect the health of more than 13,000 people during ENSO years. Despite the relatively low number of people affected by respiratory illnesses, if compared to Amazonian population, the government costs to treat such illnesses were estimated to reach US$10 million during the 1997–1998 ENSO. It is important to realize that these numbers are only based on the cases that required hospitalization. Anecdotal evidence suggests that the impact of fire and smoke to rural and urban population health is underestimated, since most of the respiratory problems, mainly in rural Amazonia, tend to be treated at home.

4. MAPPING AND MONITORING FIRE EVENTS: PAST, PRESENT, AND TRENDS

Routine active fire monitoring over Amazonia was initiated during the mid-1980s at the National Institute for Space Research (INPE) in São José dos Campos, Brazil. In July 1985, 1-km resolution images from the advanced very high resolution radiometer (AVHRR) aboard the NOAA-9 satellite were acquired and processed to provide weather and cloud information for the NASA-INPE Amazon Boundary Layer Experiment (ABLE 2A). Unexpectedly, the images showed dozens of large burnings with smoke plumes spreading for hundreds of kilometers over supposedly pristine forested areas. The ABLE 2A experiment provided the basis for the interpretation of the chemical species measured [*Andreae et al*., 1988] and also the sample cases to develop a detection technique for identifying active fires in the 4-μm spectral channel. INPE then processed the AVHRR images for 1987, which showed hundreds of fire events and massive emissions of gases and particulates to the atmosphere [*Setzer and Pereira*, 1991].

In 1989, the National System for Forest Fire Prevention and Combat (PREVFOGO) was established under the auspices of the Brazilian Institute for the Environment and Natural Renewable Resources (IBAMA). The AVHHR instrument aboard the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite series remained the primary data provider for the INPE fire monitoring system for nearly 10 years. During that time, fire detection data processed by INPE were routinely disseminated to PREVFOGO via facsimile. However, it was only after the great 1997–1998 El Niño episode that the active fire processing by INPE gained national interest. Widespread forest fires were reported for various areas across Brazilian Amazonia during the peak El Niño months with major forest loss affecting Roraima state [*Elvidge et al*., 2001]. As a result, a national program was established immediately after the 1997–1998 El Niño episode as a response from the Brazilian federal government to environmental concerns raised by the national and international communities in face of the damages caused by the fires. In May 1998, the Fire Prevention and Control Program for the Arc of Deforestation (PROARCO) was established under the auspices of IBAMA with financial support from the World Bank. The PROARCO program was designed to make intensive use of satellite remote sensing products and geographic information systems technology to provide near real-time active fire information and fire monitoring statistics for Brazilian Amazonia. The fire information was intended to support the regional strategic plans and help guide the field activities of PREVFOGO.

Following the establishment of PROARCO, the remote sensing active fire database for Brazilian Amazonia was gradually improved by incorporating additional satellite systems into routine fire monitoring operations undertaken by IBAMA (http://www.dpi.inpe.br/proarco) and INPE (http://www.cptec.inpe.br/queimadas). The original pre–El Niño fire monitoring capacity based on a single AVHRR sensor was rapidly enhanced by incorporating data from (1) the GOES 4-km resolution imager positioned at 75ºW longitude along the equator (GOES East), (2) the 1-km resolution Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the EOS-AM (Terra) and EOS-PM (Aqua) polar orbiting satellites, (3) the 0.55-km resolution DMSP nighttime-based detection using the Operational Linescan System (OLS) visible channel data, (4) the 2.4-km resolution visible and infrared scanner (VIRS) aboard the Tropical Rainfall Measuring Mission (TRMM) low inclination orbit satellite, (5) the European geostationary Meteosat Second Generation (Meteosat-9) 3-km resolution instrument, and finally, (6) by incorporating data from additional AVHRR instruments flying aboard other NOAA polar orbiting satellites. The combined use of multiple polar orbiting and geostationary satellites was an important step toward reducing the response time during fire emergencies, while permitting improved delineation of fire spatial and temporal dynamics through the integration and comparison of multiple observations and the production of basin-wide fire statistics [*Schroeder et al*., 2005].

Most remote sensing imaging systems with fire monitoring capability rely on the 4-μm spectral region to detect active fires. Active fire detection performance varies primarily as a function of a sensor's spatial resolution and algorithm used. Satellite sensors measure the total instantaneous fire-emitted radiation, which depends on the size and intensity of the flaming front. In fact, the actual flaming area of a vegetation fire will normally be constrained to a few tenths of a hectare, which, compared to the spatial resolution of the instruments described above, will represent only a small fraction of the projected pixel area. Consequently, coarser resolution satellite data will typically be associated with reduced detection capacity as larger flaming areas, or alternatively more intense fires, will be required to create a distinguishable signature from the area-averaged pixel data [*Schroeder et al*., 2008b]. In this respect, the improved sensitivity to smaller fires provided by single daytime and nighttime observations from moderate resolution polar orbiting instruments serve to complement the high observation frequency data provided by coarse spatial resolution geostationary satellites. Application of different fire detection algorithms also provides the user community with additional fire product versions to choose from [*Morisette et al*., 2005]. Despite having the longer satellite time series currently available, AVHRR data may be impacted by the systematic orbital drift of NOAA 7, NOAA 9, NOAA 11, and NOAA 14 satellites, which can have important consequences for interannual fire analyses [*Csiszar et al*., 2003]. Currently, the AVHRR/NOAA 12 and the TRMM data provide two of the longest continuous fire data records available for Amazonia (approximately 10 years of data acquisition) systematically produced from a single satellite instrument and algorithm architecture. Despite its shorter time series of active fire data records for Amazonia, the MODIS instrument routinely provides very accurate image navigation information, which can be useful when finer spatial analyses are desired [*Wolfe et al*., 2002].

Despite the sizeable number of products that are available for Brazilian Amazonia, very little information is at hand to characterize the individual burning events that are described by the active fire detection products. Sensor limitations commonly associated with low saturation levels prevent estimation of important parameters such as fire temperature and size for a significant fraction of the events mapped. However, alternate products can be used to help characterize the extent of burning at a particular location beyond the inherent limitations associated with the active fire data. These complementary products include burnt area mapping [e.g., *Barbosa et al*., 1999; *Grégoire et al.*, 2003; *Roy et al*., 2002; *Simon et al*., 2004] and fire radiative power estimates [*Kaufman et al*., 1996; *Wooster et al*., 2005]. The burnt area mapping derived from MODIS is the first peer-reviewed global-scale product to be incorporated into the routine land surface products processing stream of a major satellite mission. Although preliminary assessment of its performance included part of Amazonia [*Roy et al*., 2005], further research is still required to fully characterize the potential for fire monitoring applications over the region. Fire radiative power estimates are another relatively recent application in the field of remote sensing. Previous studies have demonstrated its effectiveness in quantifying the rates of biomass combustion for vegetation fires, which, in turn, can be used to derive estimates of gaseous emissions from burning [*Kaufman et al*., 1996; *Wooster*, 2002; *Wooster et al*., 2003]. Application of fire radiative power estimates to derive total fire emitted radiant energy [or fire radiative energy (FRE)] is dependent on the frequency of observations (for integration purposes) for which geostationary instruments are well suited. However, the coarse resolution and low saturation level of most imaging instruments aboard geostationary platforms, along with the problem of cloud coverage, may still prevent full derivation of FRE estimates in many cases [*Roberts et al*., 2005].

Future remote sensing systems with active fire monitoring capacity include two new series of polar orbiting and geostationary satellites which should enable routine imaging of Amazonia for the next two decades. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace the existing AVHRR sensor series with improved spatial, spectral, and radiometric resolutions. The proposed NPOESS orbital configuration is expected to produce three daytime image acquisitions with Equator crossing times of 0930, 1330, and 1730. The first NPOESS instrument is expected to be operational by early 2010s. The Geostationary Environmental Operational Satellite Series-R, planned for launching by early 2010s, will replace the existing GOES imager series. GOES-R should provide improved spectral, spatial, and temporal resolution data, becoming an important tool for monitoring fire activity over Amazonia at very high observation frequencies (typically ≤15 min for full hemisphere coverage). Another new trend in remote sensing deals with the concept of small satellite missions, which are targeted at instruments dedicated to map a fewer number of parameters (see *Briess et al*. [2003] for an example of a small satellite mission dedicated to active fire detection). Their major advantage is reduced costs relative to other multimission platforms while satisfying the specific needs of a particular measurement (e.g., spectral and spatial sampling issues).

5. SPATIAL DISTRIBUTION, INTERANNUAL VARIABILITY, AND CHANGE RATES

As described in the previous sections, the spatial distribution of vegetation fires in Brazilian Amazonia is strongly associated with human presence as well as with the regional biophysical conditions. Satellite maps of vegetation fire activity show that approximately 40% of the region is under the influence of fires (Plate 1). Vegetation fires are primarily concentrated in the southern and eastern parts of the basin including the states of Rondônia and Mato Grosso (to the south) and Tocantins, Maranhão, and eastern Pará (to the east) (Table 1). In those areas, improved infrastructure, in particular, the road network, serves to promote an accelerated process of land conversion and the more intensive use of land where fires play a significant role [*Laurance et al*., 2001; *Nepstad et al*., 2001; *Alencar et al*., 2004; *Arima et al*., 2007; *Sorrensen*, 2004] (see also Figure 3).

While fires appear to be widely distributed in space especially in areas such as the states of Tocantins and Maranhão, analysis of their return frequency shows the existence of more complex spatial patterns (Plate 1). These patterns are a function of the type of application involved with the use of fire and therefore will reflect the characteristics associated with the two main categories described above, namely, conversion and maintenance fires. Conversion fires will usually be related to high intensity, long-lasting burning episodes as a result of larger fuel loads, and their distribution in space will tend to form a continuum of gradually expanding areas following the deforestation patterns (see section 5). Maintenance fires, however, will tend to be associated with lower intensity and shorter burning episodes which are typically scattered in space following the rural landscape configuration. These considerations make the detection of conversion fires from remote sensing imaging systems more likely, therefore creating clusters of high fire frequency over areas where forest conversion continues for two or more consecutive years. Under cloud-free conditions, open sky fires (e.g., conversion or maintenance) as small as 0.1 ha may be detected even by coarse resolution satellite imaging systems [*Prins et al*., 1998]. However, for low-intensity understory burning, most of the radiant energy emitted by the fire will be intercepted by the canopy and, thereby, preventing detection from infrared imaging systems. An alternative approach for mapping understory fires, which relies on the application of nighttime imaging of visible light emitters, was used over part of Roraima state to map the extent of understory burning during the 1997–1998 El Niño episode [*Elvidge et al*., 2001]. Although basin-wide annual quantification of understory active fires, which can be compared to the open sky detections, remains to be determined. Other complementary studies have used change detection techniques and spectral indices applied to high and moderate resolution satellite data for monitoring areas affected by understory fires [*Alencar et al*., 2006; *Shimabukuro et al*., 2006; *Sousa et al*., 2005]. Q6
These techniques focus on the effects of understory fires (e.g., tree mortality) as opposed to the instantaneous fire-emitted radiation to derive estimates of burning activity over closed-canopy forest and selective logging areas. Consequently, only areas where canopy damage is noticeable may be represented by those methods.

The regional climate of Amazonia is another important factor which can influence the spatial and temporal distribution

Table 1. Fractional Distribution of 0.05° × 0.05° Grid Cells With Associated Hot Spot Detections (From Plate 1) for Brazilian Amazonia and Its Nine States

Region	Number of Cells	No Detection (%)	Low Conf (%)	Med Conf (%)	High Conf (%)
Brazilian Amazonia	168,726	44.3	11.6	11.4	32.7
Acre	5,306	46.1	16.2	16.6	21.1
Amapá	4,899	61.9	12.3	11.5	14.3
Amazonas	52,082	77.3	14.6	5.0	3.1
Maranhão	11,283	3.1	3.7	12.5	80.7
Mato Grosso	30,705	13.4	11.0	19.5	56.1
Pará	41,421	38.9	10.8	10.3	40.0
Rondônia	8,201	21.3	11.0	11.9	55.8
Roraima	7,660	54.6	13.6	12.6	19.2
Tocantins	9,577	2.2	6.3	19.3	72.2

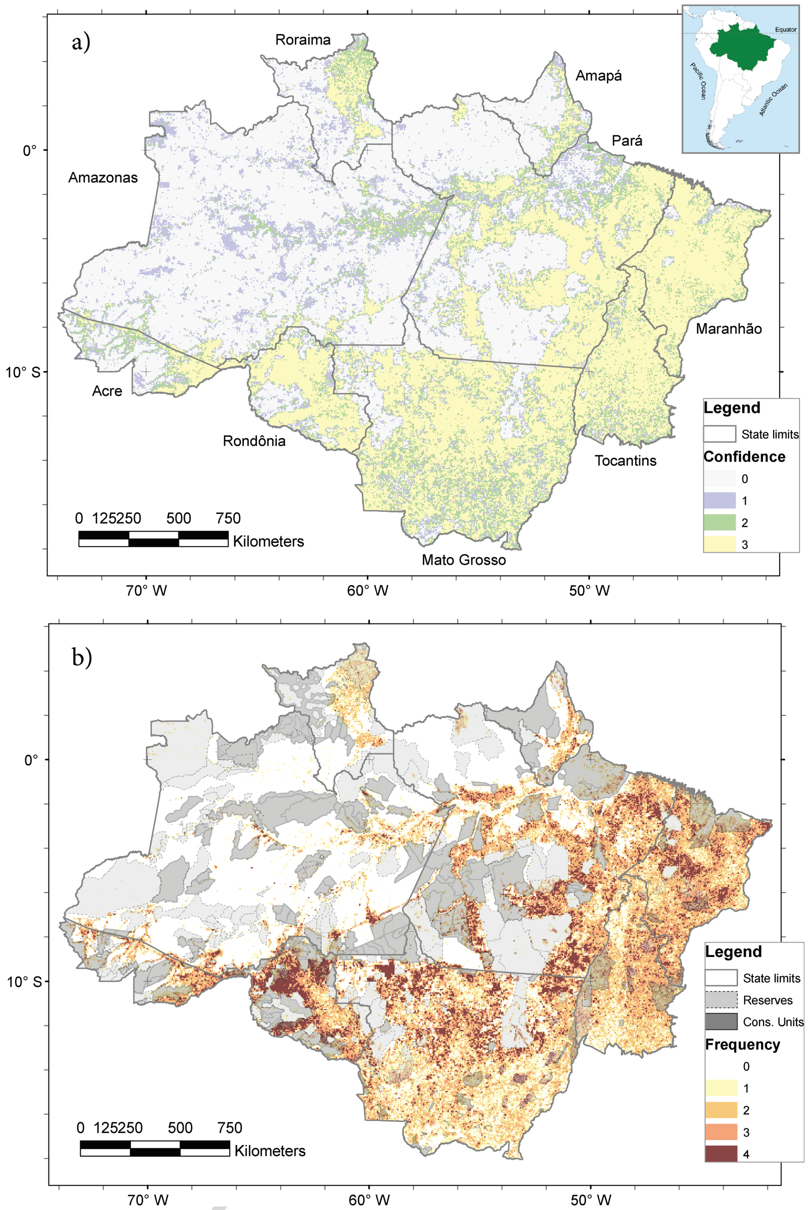

Plate 1. (a) Areas of potential fire activity as mapped by daytime and nighttime AVHRR/NOAA 12, GOES 08 and 12, and MODIS/Terra and Aqua data during 2003–2006 (4.15 million hot spots processed). Hot spot observations from all three fire products were aggregated using a 0.05º × 0.05º grid. High confidence areas are defined as those locations for which all three sensors (i.e., AVHRR, GOES imager, and MODIS) produced hot spot detections during the time period above, whereas medium and low confidence areas had two and one sensor producing hot spot detections, respectively. Areas of low confidence are particularly noticeable across Amazonas state and are usually associated with low rank detections depicted by the GOES fire product. (b) Map of active fire detection frequency derived from MODIS/Terra and Aqua daytime and nighttime overpasses during 2003–2006. Data was aggregated using a 0.025º×0.025º grid and further resampled to 0.05º × 0.05º grid using maximum value criterion. Color scheme represents the number of years with observed hot spot detection within each 0.05º × 0.05º grid cell. The distribution of indigenous reserves, and federal and state (displayed as a single layer) conservation units is also shown in (b).

of fires in the region. The average biophysical conditions of Amazonia often pose a natural barrier for vegetation fires to develop [*Uhl and Kauffman*, 1990]. Temperatures remain stable throughout the year, annual average rainfall is in excess of 2000 mm for most of the region, and the average number of consecutive rainless days during the dry season is relatively small [*Alvalá et al*., 2002; *da Rocha et al*., 2004]. These factors have a direct impact on the human activities in the region (e.g., limiting road traffic flow during the wet season) and consequently on the use of fires. Land management through fire then becomes temporally constricted and tends to follow the onset of the dry season across the basin. Along the transition zone that separates the evergreen tropical forests from the cerrado type of vegetation, the contrast between dry and wet seasons becomes more pronounced, and the rainless periods can be more than 4 months. Under such conditions, the temporal distribution of fire use may also be influenced by social, economic, and political factors which will help determine at the local or regional scale the particular timing of fire use during the dry season period. In this kind of environment, a more stratified regional pattern may result (e.g., central Mato Grosso state; Plate 2).

Land cover change and fire activity may vary as a function of economic incentives promoted by national and international market connections [*Fearnside*, 2001; *Brown et al*., 2005; *Nepstad et al*., 2006b]. For instance, the steady increase in soybean market price observed during the 2001–2004 period was followed by an equivalent increase in the total area planted in Amazonia [*Morton et al*., 2006], thereby pushing the annual deforestation rates and the number of fire detections alike. The increase in the use of fires for land clearing during the 2001–2004 period was reflected in the growing number of detections mapped over densely forested areas for that same period (Figure 1).

Major interannual variability of fire activity in Amazonia can also be associated with extreme climatic events. Events such as El Niño and the recent warming of the tropical North Atlantic in 2005 [*Marengo et al*., 2008] are prone to increase forest flammability as a result of severe drought conditions, which may develop in parts of the region. Increased forest flammability associated with higher risk of fires escaping control often lead to widespread forest fires affecting significantly large areas [*Van der Werf et al*., 2004; *Alencar et al*., 2006; *Brown et al*., 2006; *Nepstad et al*., 1999a]. Satellite active fire products will normally show strong peaks departing from the annual average in fire activity associated with such large-scale climate anomalies (Figure 1).

Some of the most recent alternatives designed to cope with the increase in fire activity in Brazilian Amazonia were associated with the adoption of specific public policies including temporary fire prohibition, increase in law enforcement, and the creation of new conservation areas. Fire prohibition

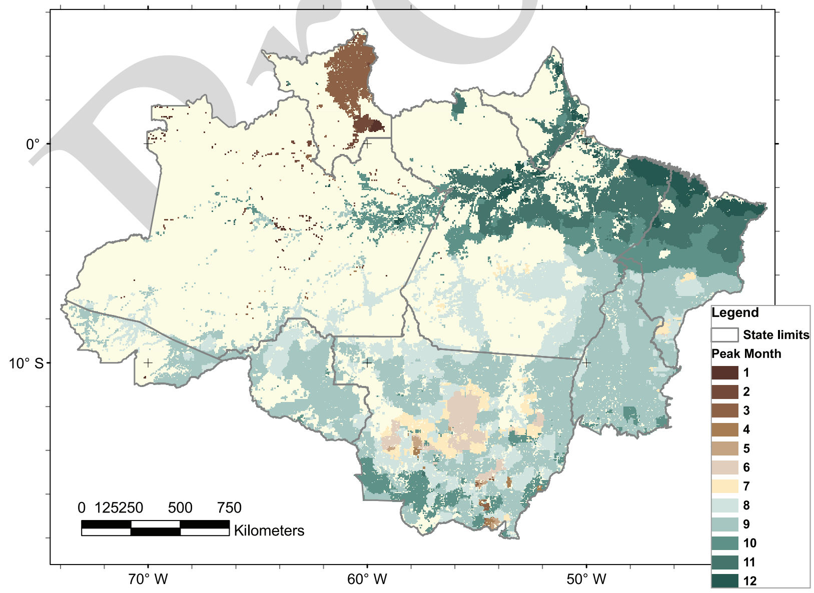

Plate 2. Map of peak month of hot spot detection as observed by MODIS/Terra and Aqua, AVHRR-NOAA 12 and GOES 08, and 12 daytime and nighttime images during 2003–2006 (4.15 million hot spots processed). Data was aggregated using a 0.05° × 0.05° grid. Only cells having hot spot detections produced from two or more sensors (medium and high confidence cells from Plate 1a) are represented on the map.

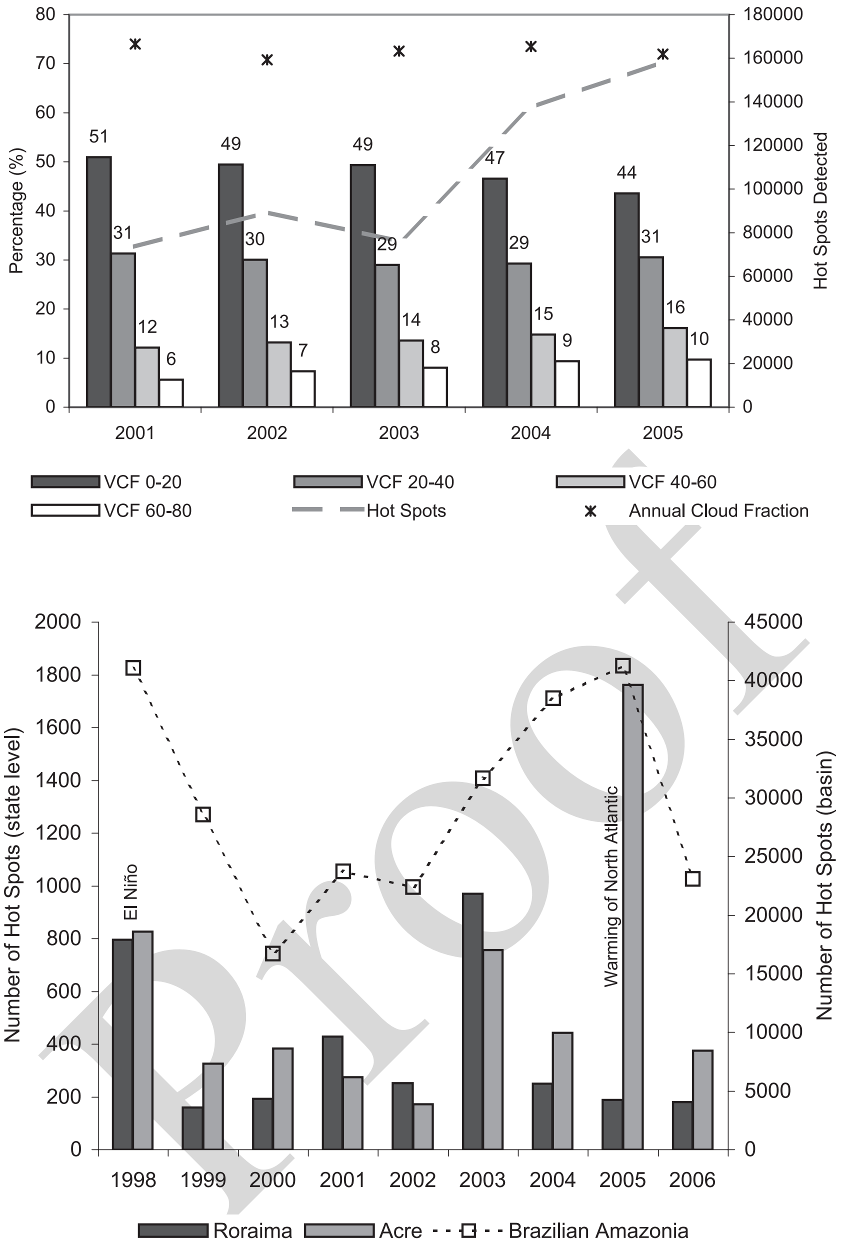

Figure 1. (a) MODIS/Terra daytime and nighttime fire product summary statistics during 2001–2005. (dashed line) Hot spot interannual variation presented as totals and (vertical bars) as annual percentage distribution using uniform Vegetation Continuous Fields (VCF) intervals. (asterisks) Basin-wide average cloud-cover fraction derived from MODIS/Terra shows little interannual variation (<4%). (b) (dashed line) Annual number of hot spots detected by the TRMM/VIRS instrument over the Brazilian Amazonia. Vertical bars describe hot spots detected over Roraima and Acre states, which were severely affected by the 1997–1998 El Niño and the 2005 warming of the tropical North Atlantic waters, respectively.

was first proposed for Mato Grosso state in 2001 and was followed by other regions in subsequent years. It is used as a preventative mechanism limiting burning at the peak of the dry season as well as an emergency response when rapid reduction in fire activity is desired [*Brown et al.*, 2006]. Successful application of a fire moratorium depends on the effectiveness of law enforcement and on community engagement. The creation of new conservation areas also depends on the effectiveness of law enforcement and park administration, and in some cases, the established areas may not withstand the threats of logging and fire [*Ferreira et al*., 1999; *Laurance and Williamson*, 2001; *Pedlowski et al*., 2005]. Pressure is building along conservation units where the surrounding forests are being depleted (see examples in Plate 1).

6. SPATIAL AND NUMERICAL RELATIONSHIPS WITH DEFORESTATION RATES

As described above, vegetation fires and deforestation activities in Amazonia are closely related. However, the numerical relationship between satellite derived hot spot counts and the spatially coincident deforestation estimates at any spatial scale remains mostly unresolved. Among the major factors limiting our capacity to establish a more accurate relationship between hot spot counts and deforestation area are:

Q7 1. Vegetation fires have a highly dynamic nature. Constant changes in fire size and temperature limit our ability to derive a mean fire property.

2. The mode of image acquisition is noncontinuous. Satellite images are usually acquired at intervals ranging from 15 min to 12 h for geostationary and polar orbiting satellites, respectively.

3. The imaging process limitations involved. Optically thick clouds can obscure fires and prevent their detection [*Schroeder et al*., 2008a].

4. The forms of burning and fire type variations. The wide range of vegetation structures and fuel loads which characterize Amazonia will influence the detection of fires accordingly [*Schroeder et al*., 2005].

Due to the limiting factors above, it is very likely that a significant fraction of the actual fires will have only a few observations made by most remote sensing products during the entire life cycle of the burning event. Consequently, the relationship between the total deforested area and the number of hot spots detected for a particular location is usually difficult to derive. Nevertheless, the spatial distribution and concentration of hot spots tend to follow the trend described by the deforestation rates (Figure 2).

Figure 3 shows the percentage distribution of hot spots detected alongside a 260-km segment of highway BR-163 near Novo Progresso in Pará state. Fire detection statistics were derived for two distinct periods (1999–2000 and 2004–2005) using seven 10-km buffers across the road's main axis. The 70-km-across subregion described by the buffers represents one of the most intact tracts of forests found in the immediate vicinity of highway BR-163 during this period. Factors such as reduced road trafficability, especially in the wet season, and the increased distance to ports and markets have limited the expansion of human activities in this region relative to other areas. For comparison purposes, the corresponding percentage distribution of the annual deforestation increment derived from higher resolution Landsat enhanced thematic mapper plus (ETM+) imagery is also plotted in Figure 3. Fire and deforestation show very similar patterns for the two periods analyzed with equivalent changes in the spatial distribution over time. Most important in Figure 3 is the progress in deforestation and fire use away from the highway and deeper into the forested areas, which suggests the intrusion of human activities in previously undisturbed areas. Absolute deforestation rates increased by a factor of three within the 5-year period analyzed, while hot spot counts went up by as much as five times. It is important to note that active fire detection products based on contextual methods, such as the one used with Figure 3, can be affected by commission errors which might reinforce the relationship with deforestation (see *Giglio et al*. [1999] for a discussion of different types of fire detection methods). These errors may be observed over deforested sites surrounded by relatively homogeneous forests as a result of the high thermal contrast between the two areas which cause a false detection to be produced [*Schroeder et al*., 2008b]. Despite the good overall agreement between the two different data sets in Figure 3, the measure of correlation describing individual episodes (i.e., the relationship between the number of hot spots detected and the area in hectares of the overlapping deforestation polygon) remains low ($r^2 = 0.54$ using 2004 data).

There has been a long debate over the relationship between roads, deforestation, and fire use in Amazonia [see, for example, *Nepstad et al*., 2001; *Laurance et al*., 2001; *Silveira*, 2001; *Câmara et al*., 2005]. Roads facilitate access to otherwise remote areas and therefore serve to promote land use expansion where deforestation and fires play a significant role. However, their importance in relation to other forces such as regional and global economic markets is still subject to major controversy. Nevertheless, as shown in Figure 3, deforestation and fires are particularly concentrated along the major road corridors in the region. Future projections of forest transformation by deforestation and fires will be influenced by the assumptions incorporated into the models, which often lead to important differences in the predictions produced. The establishment of positive feedbacks between deforestation and fires is perhaps the most important aspect which helps explain the frequently observed pattern of increased forest degradation along major road corridors. Provided that human occupation in Amazonia will continue in the decades to come, it is very likely that deforestation and fires will also become even more frequent phenomena in the region, as forest fragmentation increases. Many

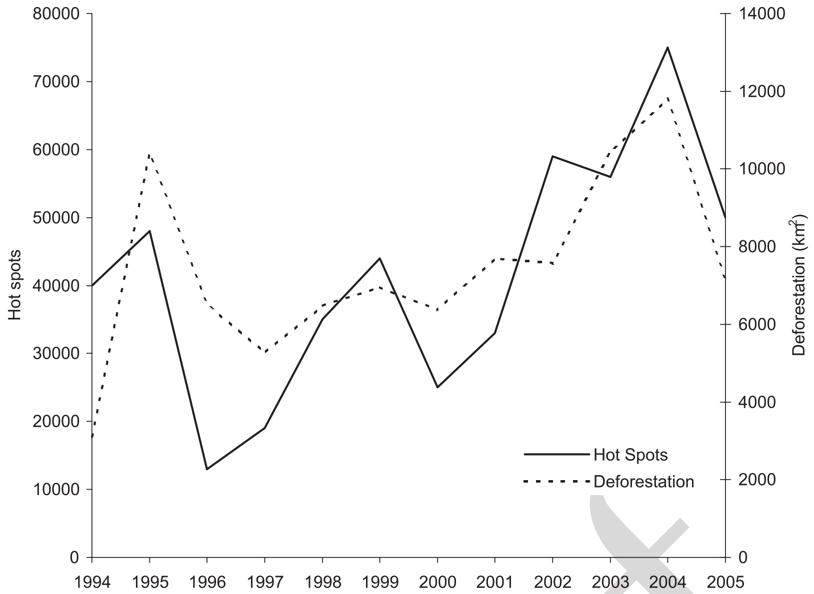

Figure 2. Deforestation estimates (PRODES) and AVHRR/NOAA 12 hot spot detections for the state of Mato Grosso during 1994–2005.

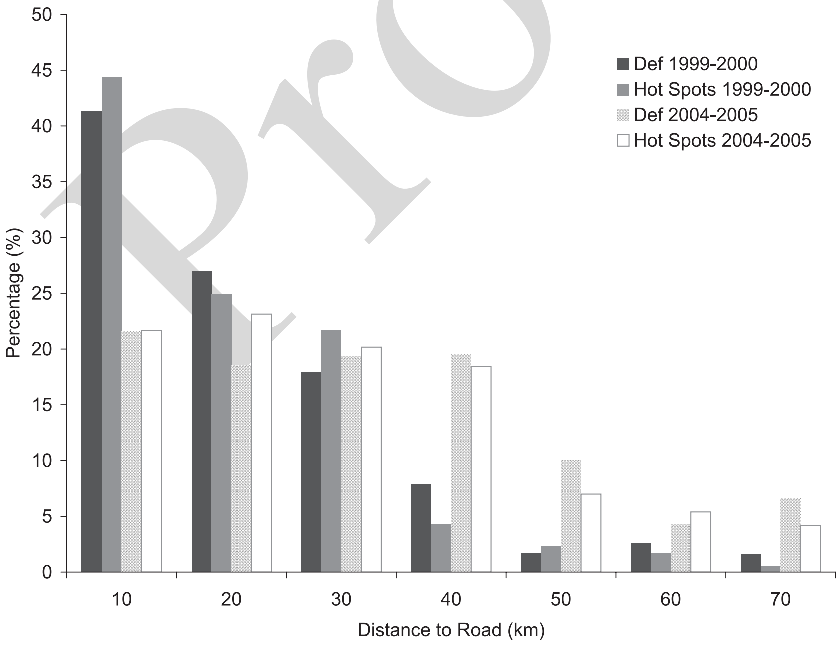

Figure 3. Hot spots detected by the TRMM/VIRS instrument and deforestation increments mapped with the Landsat enhanced thematic mapper plus (ETM+) instrument during 1999–2000 and 2004–2005 for a 260-km segment of highway BR-163 near Novo Progresso, Pará state. Values represent the percentage distribution using 10-km-wide buffer zones from the highway.

modeling studies have suggested important regional biophysical changes induced by logging and fires which could ultimately lead to a gradual replacement of forests by savanna-like vegetation as drier and warmer conditions prevail [*Nobre et al*., 1991; *Henderson-Sellers et al*., 1993; *Hoffmann et al*., 2003b].

7. CONCLUSION

As presented throughout this chapter, vegetation fires in Amazonia are very diverse in nature with highly heterogeneous spatial and temporal distributions. Fire is a fast and inexpensive tool currently used by millions of landholders in the region for converting forests into crop production and pasture as well as for managing their lands afterwards. Consequently, fires are strongly influenced by the human presence in the region. The widespread use of fires in Amazonia has important impacts on various biophysical and climate dynamics processes, which extend from landscape to global scales. Fire intrusion over previously undisturbed areas may also trigger important feedback mechanisms which can disrupt the fragile environment of evergreen tropical forests.

Major awareness of the extent of biomass burning and its associated effects over Amazonia was fostered in 1985 when the first evidences of the widespread use of fires in the region were noticed. Fire mapping and monitoring capabilities have been significantly enhanced since then, evolving from single AVHRR image monitoring in the 1980s to more than a dozen orbital platforms collecting over a hundred images every day. However, the spatial scales at which active fires occur (normally in the order of a few tenths of a hectare) and the degree of variability of fire properties as a function of time still pose significant challenges for the full characterization of the different fire regimes in Amazonia. Nevertheless, despite their limitations in terms of spatial resolution, and spectral and radiometric characteristics, which often preclude estimates of fire-related parameters such as temperature and area affected, the current suite of instruments available for active fire monitoring have been providing important information to delineate the regional aspects of fire occurrence in Amazonia.

Social scientists have gained a good understanding of the major causes and economic and social consequences of fire in Amazonia. Biologists and ecologists now understand the effects of fire in the Amazonian forest ecosystem and are able to delineate several feedback processes that emerge from the complex associations between fire and vegetation dynamics. Likewise, climatologists have successfully described the impacts of fires on regional and global climate dynamics providing groundbreaking results that magnify the importance of widespread use of fires in the tropics.

Future research methods should integrate multiple data sets to provide new avenues for improved understanding of the dynamics of fire use in the tropics. Coupled human-climate models are then required to assess the implications of vegetation fires for regional societies and global climate and to help delineate the multiple feedbacks and processes, which drive the interactions between humans and the environment.

Acknowledgments. The following fire product versions were used with Plates 1 and 2 and Figure 1: (1) AVHRR instrument aboard NOAA 12 satellite: INPE's fixed threshold algorithm; (2) GOES East imager: University of Wisconsin at Madison Wildfire Automated Biomass Burning Algorithm (WFABBA); (3) MODIS instrument aboard Terra and Aqua satellites: NASA's MOD14 "Thermal Anomalies" product. Q8

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