P1E.2

LANDSCAPE FRAGMENTATION AND FIRE VULNERABILITY IN PRIMARY FOREST ADJACENT TO RECENT LAND CLEARINGS IN THE AMAZON ARC OF DEFORESTATION

Ernesto Alvarado[1*], David V. Sandberg[2], Joao Andrade de Carvalho Jr.[3], Ralf Gielow[4] , Jose Carlos Santos[4]

[1]Fire and Environmental Research Applications, College of Forest Resources, University of Washington, Seattle, Washington, [2]USFS PNW Station, Fire and Environmental Research Applications, Corvallis, Oregon, [3,4]Universidade Estadual Paulista, Guaratinguetá, Sao Paulo, Brazil, [4]Instituto Nacional de Pesquisas Espaciais, Cachoeira Paulista, SP, Brazil

1. INTRODUCTION

Tropical forests throughout the world are disappearing or deteriorating to a very rapid pace. Among the most significant causes is the change in land use by the conversion of land use to agriculture, pasture, or urbanization. Selective logging and natural factors also account for a large portion of tropical forest loss. Although there are large efforts by national and international governments and agencies to curtail the rapid loss of such forests, there is a disturbing increasing trend of loss of tropical forest resources. There are apparent successes in government programs, but gains seem only temporary. For instance, massive deforestation occurred in the Brazilian Amazon forest during the 1970s and 1980s. It does continue but slowed down on the 1990s due to Brazil's government policies. However, recent assessments show that it is on the increase again and now with different spatial patterns than before (Skole and Tucker 1993, INPE 2002, INPE 2003, Laurance et al. 2001).

Occurrence of catastrophic wildfires in the last few decades in different parts of the world has raised awareness of devastating local and regional effects and the potential impact across international borders.

*Corresponding Author Address: Ernesto Alvarado. Fire and Environmental Research Applications. College of Forest Resources, University of Washington. Pacific Wildland Fire Sciences Laboratory. 400 N 34th Street, Seattle, WA 98195. Email: alvarado@u.washington.edu

In addition, a steady increase of wildfire risk has been detected in the last couple of decades in temperate and tropical ecosystems. Noticeably, uncontrollable wildfires in the tropics have increased in number and extent at rates higher than temperate forests. Ordinarily, undisturbed tropical rain forest is considered a fireproof ecosystem, however, severe fires occur during sustained droughts when the ecosystem is dry enough to sustain smoldering combustion, or when the canopy is disturbed by natural events or human activities. Those climate and forest conditions are concurring more often in the tropical world.

The 1998/99 wildfire seasons in Mexico, Central America, Amazônia, and several other countries across the world signaled how vulnerable tropical ecosystems are becoming to wildfires and that the immediate effects can be felt across borders. The tropical southern Mexico and the state of Roraima in the northern Brazilian Amazon were heavily impacted during that wildfire season (Cairns and others 1998; Kirchhoff and Escada 1998). Extensive damage has also been observed in several parts of the Amazonian forest. These severe and extensive wildfires are a threat to the ecological integrity, biodiversity and sustainability of tropical forests. Those severe fire seasons also have shown that some land use/land cover types are more vulnerable than other types and that generalizations cannot be made in terms of flammability or carbon emissions from tropical ecosystems.

An increasing amount of fire usage, coupled with large areas of forest vulnerable to fire, creates a new threat to the integrity and sustainability of the tropical forests in Amazonia and elsewhere in the tropical world. Forest wildfires that start form from escaped agriculture and rangeland fires are becoming more common throughout the tropical world. Fire has been observed to spread under the canopy for long distances and smolder for long periods on rotten trunks where it can remain active for long periods. Those accidental fires cause approximately one-half of the area burned in the Amazon forest of Brazil, and are often associated fires that start in adjacent areas cleared for agriculture or transportation corridors (Nepstad and others 1999, Uhl and Kauffman 1990)

2. OBJECTIVES AND STUDY AREA

The Fire and Environmental Research Team (FERA) of the US Forest Service, Seattle, Washington is engaged in cooperative programs on wildfires in the United States, Brazil, Mexico, and Bolivia. The research is directed to develop a globally consistent decision support system for fire management, ecosystem restoration, and global change response to wildfires. These cooperative projects are sponsored in the US by the USFS International Programs, USAID, NSF, and in Brazil by FAPESP, UNESP, and INPE. Participants of these cooperative projects include researchers and students from the FERA Team of the US Forest Service, University of Washington, Brazil's Instituto Nacional de Pesquisas Espaciais, Universidade Estadual de Sao Paulo, Universidade de Brasilia, and the Universidad Estadual do Mato Grosso, and the Instituto Nacional de Pesquisas da Amazonia. Cooperation started since 1997 and has included studies on flammability assessment of primary, logged and fragmented tropical forest, prediction of biomass consumption and smoke emissions from fires in tropical ecosystems, and development of a thermodynamic model of flaming, smoldering, and residual combustion.

This paper presents the results of a flammability study conducted during 1998, 1999, 2001, 2002 and 2003. The study is conducted as part of a series of small experimental burns to study biomass combustion and carbon release rates from deforested Amazon forest. This particular study monitored the change in forest vulnerability to fire on the interface between primary forest and recent deforested patches near Alta Floresta in the state of Mato Grosso. The objective of the study is to identify the conditions necessary to self-sustain fire spread in closed-canopy forests in the seasonally dry Amazon forest along the Arc of Deforestation. The purpose of establishing the flammability experiment on the edge of the biomass combustion experimental burns is also to measure the effect of heating from burning in adjacent clearings on the flammability of primary forest fuels and to use the fire from the slash burn as the ignition source for the understory fire.

The experiments occurred in "terra firme" forest sites located near the city of Alta Floresta, Mato Grosso, Brazil. Alta Floresta is located in northern Mato Grosso in the Arc of Deforestation. It is a city that was funded almost 30 years ago. It is located in a region that experiences one of the highest rates of deforestation and fire occurrence. In 1998, 1999 and 2001, the experiments were conducted at the Caiabi farm. In 2002 and 2003, the fire investigation was conducted at the Ouro Verde farm. The geographical coordinates of Caiabi are 09° 58' S and 56° 21' W (Figure 1). In 2002, Brazil's fire regulations allowed burning only after October 1 in 2002, by then the rainy season had started, which did not allow a successful burning. In 2003, a wildfire that escaped from a nearby pasture fire burned without control in the forest understory for several days and burned the experimental plot before the planned burn date.

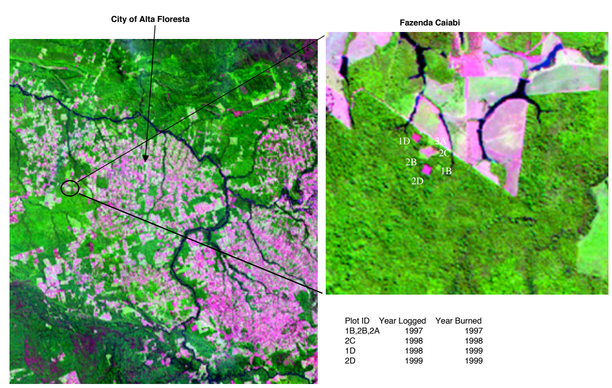

Figure 1. Location of experimental combustion and flammability plots in Alta Floresta and the Caiabi farm in Brazil. Landsat 7 image courtesy of INPE.

Results regarding biomass consumption and carbon release rates of the 1997-1999 set of tests have been published by Carvalho *et al.* (2001). All the experiments followed the same procedure of previous ones carried out in Manaus, Amazonas (Carvalho *et al.,* 1995, 1998), and in Tomé Açu, Pará (Araújo *et al*., 1999). Results of 2002 and 2003 are presented in a companion paper presented in these proceedings. A broad set of data and discussions concerning biomass burning in the Amazon region can also be found in the papers by Crutzen and Andreae (1990), Ward *et al.* (1992), Fearnside *et al.* (1993), Kauffman *et al.* (1995), and Fearnside (2000).

During the experiment, we monitored fuel moisture drying rates, microclimate, regional weather, and changes in canopy closure. Those conditions were monitored along a transect from the deforested patch into the forest during the entire dry season from the time of timber felling in May until the experimental burns occurred in late August/early September of the same year. This logging-drying-burning protocol is a common practice used by farmers in Amazonia. During the slash fire, we monitored fire behavior and depth of fire spread in the undisturbed forest from the edge of land clearing.

Field sampling methodologies included monitoring fuel moisture and weather changes along four transects under the forest canopy. The deforested patch was always approximately a square, thus, the monitoring transects were laid out perpendicular to the center of each one of the sides of the square. A transect consisted of the following monitoring stations: the center of the deforested patch for the combustion experiments, the edge between the deforested patch and the forest (0 m), 15 meters, 30 meters, and 45 meters from the edge. The transects were installed before the tree felling, the equipment was picked up for the tree felling and reinstalled the day after the felling. The fuel moisture and weather were monitored from the end of May or early June to the day before the fire in late August or early September. In 1999 the sensors were re-installed for an additional month.

Litter moisture was monitored by placing litter from the site in nylon mesh bags. The bags were weighted three times a week. Litter was replaced several times during the season and oven-dried to obtain moisture content. Three sets of 10-hour fuel sticks were placed in the monitoring station and weighted at the same time than the litter. One air temperature/relative humidity sensor (Hobo®) was installed per station. Temperature and relative humidity was monitored every hour for the entire duration of the experiment. We used the LAI-2000®, Plant Canopy Analyzer to monitor changes in leaf area index every seven days from June to September. Few days before the fire, a firebreak line was constructed at a variable distance (up to 100 meters) from the edge from the deforested patch to ensure that an accidental fire would not escape into neighboring pastures. Fire ignition for the understory fires in the undisturbed fire came form the burning patch where the combustion experiments were conducted. A paper by Andrade and others in these proceedings reports fire characteristics from those fires. Understory fires were monitored until they extinguished or were mopped-up when they reached the firebreak line.

4. DEFORESTATION, LANDSCAPE FRAGMENTATION, LOGGING AND FIRE HAZARD IN TROPICAL FORESTS

4.1 Landscape Fragmentation and Fire

Over the last 30 years, the international science community has focused in Brazil because of the global impact of deforestation, landscape fragmentation, fire vulnerability, and smoke emissions. The Brazilian Amazon experienced a high rate of deforestation in the 70s, however, current estimates provided by the Brazil's Instituto Nacional de Pesquisas Espaciais (INPE) (INPE 2002; INPE 2003) signal that it is still a difficult problem to solve. INPE estimates that the deforestation rate for the 2000/2001 reached 18,166 squared kilometers. Initial estimates from 50 LANDSAT scenes for 2001/2002 indicate that the rate may be higher than the previous biennium. INPE also estimates that during 1995, 20.5 million hectares of the Brazilian Legal Amazon burned. Extensive deforestation in the Amazon basin has created a highly fragmented forest in regions with an extensive rate of land use conversion and use of fire for land clearing and agriculture and grassland maintenance.

The forest on the interface with land clearings suffers drastic changes in micro weather, vegetation composition and structure, and ecological processes. Those altered vegetation and environmental conditions of the interface are favorable for allowing sustaining combustion under the forest canopies after a prolonged dry season.

The threshold conditions for fire spread and the characteristics of fire in the tropical forests of the Brazilian Amazon are important determinants of fire effects on the ecosystem and biogeochemical cycles. The combination of increased fire usage, larger areas of forest vulnerable to fire, and predicted severe droughts under several climate change scenarios creates a potential threat to the integrity and sustainability of the tropical Amazonia and elsewhere in the tropical world.

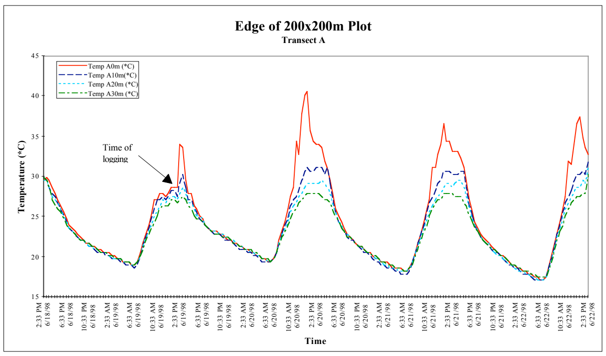

Figure 2 Air temperature profile after logging along a transect from a recent land clearing into the forest at the Caiabi farm near Alta Floresta Mato Grosso, Brazil .

These recently created interfaces suffer drastic microclimate changes soon after the tree felling during the land clearing practices (Figure 2). The data displayed in this figure shows the immediate effect in temperature for the first four days after the land clearing. Relative humidity also shows a similar pattern. For the first few days, the effects can be detected only on the edges and for a few meters inside the forest. However, as the dry season continues, the drier and warmer conditions can be experienced deeper into the forest. For those first few days, the air temperature at mid-day on the edges can be five degrees higher than deeper into the forest. Difference in air relative humidity for the same hours can be up to 40% between the edge and inside the forest. Under those conditions, fuels start to become drier. However, because the land clearings occur mostly at the end of the rainy season in this region, there is enough air humidity at night to recharge ambient, soil, and fuel moisture. Consequently, flammability increase on these few days may not be significant. Additionally, fuels on the recent land clearing will be green and will not ignite. This statement will likely not hold true if the land clearing was created in a previous years and the fuels have cured for long time. Thus, in that case, only a short drying period may be needed to ignite cured biomass in land clearing from previous years.

Difference between the edge and inside the forest becomes sharper by the end of the dry season. Average air temperature at 45-meters inside the forest can be 10 degrees C lower than the edge and relative humidity can be 30% higher inside the forest from 11 AM to 3 PM. Figure 3 shows the average air relative humidity during the hours when the forest is more flammable and when the likelihood of escaped fires is higher. A similar pattern is reflected in the air temperature, which is not displayed in this paper. Leaf area index also decreases seasonally but is more evident near the edges. Although the correlation of flammability with leaf area index is not as strong as expected, it shows a decreasing trend. Moreover, a phenomenon that was observed in 1999 during a short term cold front passage in Amazonia, the leaf area index showed a noticeable decrease because of the leaf shedding due to a drastic drop in temperature. A decrease in leaf area index may be reflected in the availability of more litter fuel on the forest floor available for an understory fire.

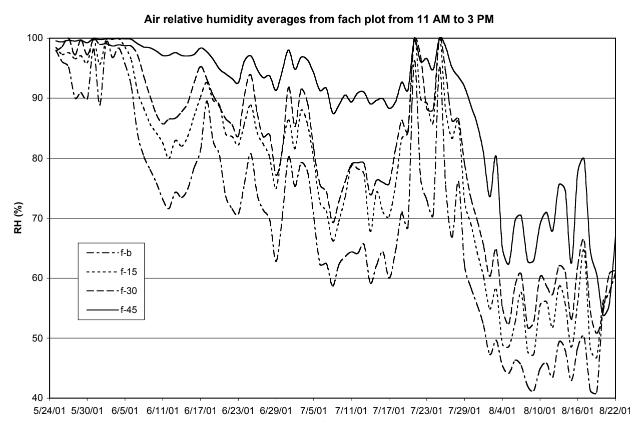

Figure 3. Average RH from 11 AM to 3 PM on a transect from the edge of a land clearing into the forest at the Caiabi farm, Alta Floresta Mato Grosso, Brasil.

The micro weather conditions along the transect are also reflected in differences in fuel moisture content. For illustration purposes, we present in Figure 4 the weight variation of fuel moisture stick analogs that represent an idealized 10-hour fuel particle. As it was observed with relative humidity and temperature, fuel moisture for the 10-hour sticks follows the same pattern. The driest fuel conditions are registered at the center of the experimental land clearing, followed by the edge. Inside the forest, the difference between 30 and 45 meters is evident only when it is dry. Early in the dry season, or after a rainfall, the fuel moisture difference between those two points is not evident. Similar patterns were also observed in litter moisture.

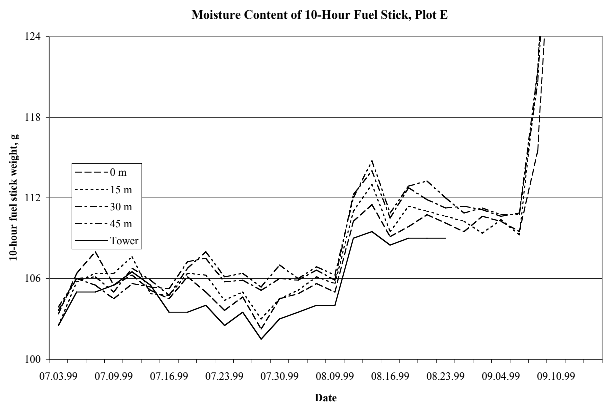

Figure 4. Variation in weight of 10-hour fuel sticks on a forest/land clearing transect at the Caiabi farm, Mato Grosso, Brazil. Fuel moisture content is calculated by the wet weight-100.

Fires that burned in the understory from the experimental land clearing fires can penetrate for only a few meters to over 100 meters inside the forest in these recently created interfaces. Figure 6 shows a pattern of fire-spread depth from the land clearing edge. During extreme dry years, or when the land clearings are adjacent to old land clearings, as it was observed in 1997, fire depth can reach up to 200 meter of depth from a 100 m x 100 m slash fire plot. We have observed forest fires in the region that escape from grassland fires and propagate in the understory for several kilometers, mostly by the end of the dry season. Fires that escape into the forest understory from pastures or slash burns usually exhibit a slow rate of spread. These slow spreading fires represent a challenge for the current fire behavior models because the flames spread under very limiting conditions, similar to those observed in Alta Floresta. Description of the observed fire behavior is presented by Andrade and others in these proceedings.

4.2. Logging and Fire

Little is known on the effects of deforestation and logging on fire vulnerability of the primary and secondary forests not only along the Amazonian arc of deforestation or ecotones with savanna type vegetation, but also in the interior Amazon basin where forest may be wetter. Ordinarily, undisturbed tropical rain forest is considered a non-flammable ecosystem. Nevertheless, paleoecological evidences show that fires have occurred for thousands of years (7,000 to 4,000 years and during the Holoceno) on these ecosystems throughout the tropical world (Cordeiro and others 2000; Saldarriaga and West 1986, Sanford et al. 1985). Cordeiro and colleagues suggest that the recent carbon deposition associated with land use change in Alta Floresta is similar to carbon deposited during the Holocene drought. It is likely that those fires occurred during extremely dry years. Models that predict global climate change forecast that those extreme climate conditions may be more recurrent in the future. Although fires in the tropical ecosystems have been scarcely studied, several investigations are under way to identify the conditions that make the forest flammable and allow the fuels to sustain fire spread, and to evaluate the reduction of fire hazard in forest stands under the low impact harvesting regimes for several years after the logging. Similar experiments will be started in 2004 in the tropical deciduous forests of Bolivia.

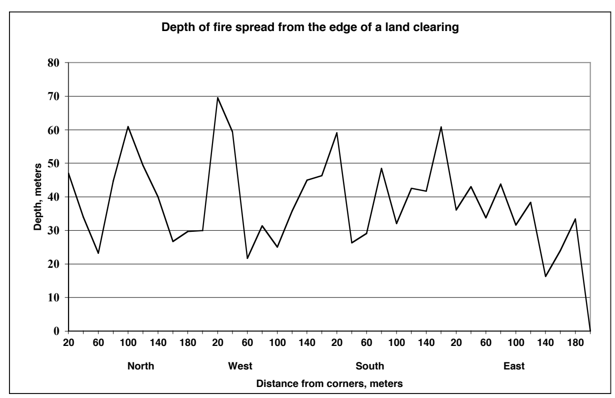

Figure 5. Depth of understory fire spread from the edge of a primary forest with an ignition source from an experimental slash burn in Alta Floresta, Brazil in 2001. The slash burning unit was a 200 x 200 m plot.

Trees in temperate forests have developed fire resistance features. However, trees in tropical forests do not have those features. Therefore, even a low intensity fire is lethal for many of the tree species. Undisturbed evergreen tropical forests are able to maintain dense lush leaf canopies during the drought season throughout Amazônia that may extend up to 5 months (Nepstad et al. 1994). That condition prevents litter, downed woody fuels, and understory vegetation of reaching the low moisture contents that make it fire susceptible. In normally drier sub regions along the "Arc of Deforestation", or ecotones with the savanna type vegetation, trees shed leaves to conserve moisture during very dry periods, allowing more sunlight and wind to penetrate the canopy and hasten the drying of fuels. This effect is more evident on the forests along the edges of land clearings where agriculture and ranching are practiced in a permanent basis.

Pressure on the Amazon forest will continue increasing as a natural response to Brazilian population growth, and to sustain the population already living in the basin. Fires set to clear land for agriculture and pastures often spread into adjacent logged areas and even into the primary forests, and many of these forests will not then regenerate to their original condition. It is to be hoped that some of the negative impacts will be relieved by the application of improved management techniques, such as low-impact harvesting, and the more judicious use of fire.

Land clearing and harvest of moist tropical forests inevitably increases the risk of destructive forest fires on the remaining forests. The potential to intensify the fire regime so severely that tropical forests are irreversibly replaced by Cerrado or other biomes is a serious problem in ecotonal areas along the "Arc of Deforestation" extending from eastern Pará to central Bolivia (Negreiros et al. 1998).

Replication of such an intensive studies is almost impossible. Thus, when regional or global assessments of flammability, smoke emissions are needed, results from fire studies in Alta Floresta can be extrapolated to relatively similar regions in the tropical world.

5. LITERATURE

Araújo, T.M.; Carvalho, J.A.; Higuchi, N.; Brasil, A.C.P.; Mesquita, A.L.A., A tropical rainforest clearing experiment by biomass burning in the state of Pará, *Atmospheric Environment.*, 33(13), 1991-1998, 1999.

Cairns, M. A.; W. M. Hao; E. Alvarado; P. K. Haggerty. 2000. Carbon emissions from spring 1998 fires in tropical Mexico. In Proceedings of the Joint Fire Conference and Workshop: Crossing the Millennium: Integrating Spatial Technologies and Ecological Principles for a New Age in Fire Management. June 15-17, 1999. Boise Idaho. The University of Idaho. Vol. I. pp. 242-248.

Carvalho, J.A.; J. M. Santos; J. C. Santos; M. M.; N. Higuchi. 1995. A tropical rainforest clearing experiment by biomass burning in the Manaus region, Atmospheric Environment, 29, 2301-2309.

Carvalho J.A.; N. Higuchi; T. M. Araújo; J. C. Santos. 1998. Combustion completeness in a rainforest clearing experiment in Manaus, Brazil, Journal of Geophysical Research, 103(D11), 13,195-13,200.

Carvalho J.A.; F. S. Costa; C. A. G. Veras; D. V. Sandberg; E. C. Alvarado; R. Gielow; A. M. Serra; J. C. Santos. 2001. Biomass fire consumption and carbon release rates of rainforest-clearing experiments conducted in Northern Mato Grosso, Brazil, Journal of Geophysical Research.

Cordeiro, R. C.; B. Turcq; A. Sifeddine; J. A. Capitâneo; A. O. da Silva. 2000. Incêndios Amazônicos: uma abordagem em diferentes escalas de tempo. In. LBA First Scientific Conference. Belem, Para. June 26-30, 2000. Pag. 221.

Crutzen, P.J.; M. O. Andreae. 1999. Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biochemical Cycles. *Science*, 250:1669-1678.

Fearnside, P. M. 1990. Fire in the tropical rain forest of the Amazon basin. In Fire in the Tropical Biota. Ecological Studies, Vol. 48. Edited by J. G. Goldammer, pp 106-116. Springer-Verlag, New York.

Fearnside, P.M. 2000. Global Warming and Tropical Land-use Change: Greenhouse Gas Emissions from Biomass Burning, Decomposition and Soils in Forest Conversion, Shifting Cultivation and Secondary Vegetation. *Climatic Change*, 46(1-2):115-158.

INPE. 2003. Preliminary data on deforestation for 2001-2003 in the Brazilian Amazon forest. Data obtained from http://www.obt.inpe.br/prodes_2001_2002.htm.

INPE. 2002. Monitoreamento da Floresta Amazonica Brasileira por Satelite. Relatorio ano 2000-2001. Data available at http://www.inpe.br/Informacoes_Eventos/

Kirchhoff, V.W.J.H; Escada, P.A.S. 1998. O megaincendio do seculo/The wildfire of the century: 1998. TRANSTEC Editorial, Sao Jose dos Campos, SP.

Kauffman, J.B.; D. L. Cummings; D. E. Ward; R. Babbitt. 1995. Fire in the Brazilian Amazon: Biomass, Nutrient Pools, and Losses in Slashed Primary Forests. *Oecologia,* 104:397-408.

Laurance W. F.; M. A. Cochrane; S. Bergen; P. M. Fearnside; P. Delamonica; C. Barber; S. D'Angelo; and T. Fernandes. 2001. The future of the Brazilian Amazon. Science 2001 5503(291): 438-439.

Negreieros, G.H.; D. Nepstad; D. Sandberg; E. Alvarado; T. Hinckley; M. Pereira. 1998. Fire along transition between the Amazon forest and the Cerrado ecosystems. In: Proceedings of the 13th conference on fire and forest meteorology; 1996 October 24- November 2; Lorne, Australia.

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

Nepstad, D. C.; A. G. Moreira; A. A. Alencar. 1999. Flames in the Rain Forest: Origins, impacts and alternatives to Amazonian Fire. The Pilot Program to Conserve the Brazilian Rain Forest. 190 p

Saldarriaga, J. G.; D. C. West. 1986. Holocene fires in the northern Amazon basin. Quaternary Research 26:358-366.

Sanford R. L.; J. Saldarriaga; K. E. Clark; C. Uhl; R. Herrera. 1985. Amazon rain forest fires. Science 227:53-55.

Skole, D.; C. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 and 1988. Science 260(25 June): 1905-1910

Uhl, C.; J. B. Kaufman. 1990. Deforestation, fires susceptibility, and potential tree responses to fire in the Eastern Amazon. Ecology, 71(2): 437-449.