Fire in the Brazilian Amazon Forest and Mexico's Protected Areas

E. Alvarado 1, D. V. Sandberg 2, J. Andrade de C. Jr. 3, R. D. Ottmar 2, E. Jardel P. 4, J. M. Frausto L.5

[1] FERA, College of Forest Resources, University of Washington. Seattle, WA, USA.
[2] USDA PNW Research Station. Fire and Environmental Research Applications (FERA). Seattle, WA, USA.
[3] Universidade Estadual do Sao Paulo and Instituto Nacional de Pesquisas Espaciais. Cachoeira Paulista, Sao Paulo, Brasil
[4] Centro Universitario de la Costa Sur, Universidad de Guadalajara. Autlan, Jalisco Mexico.
[5] Fondo Mexicano para la Conservacion de la Naturaleza. Mexico

Abstract

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. In addition, a steady increase of wildfire risk has been detected in the last couple of decades in temperate and tropical ecosystems of the world. Uncontrollable wildfires in the tropics have also 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 1998/1999 wildfire seasons in Mexico, Central America, Amazônia, and several other countries across the world signaled how vulnerable are tropical ecosystems to wildfires and that the immediate effects can be felt across borders. These severe wildfires are also a threat to natural protected areas that have been established to preserve biodiversity and populations of rare, threatened and endangered species, and unique plant communities. Those extreme fire seasons also have shown that some land use/land cover types are more vulnerable than others. Generally, open/fragmented forests and perturbed areas are more heavily impacted. Total prompt emissions during peak events add a significant amount to the region's average annual net C emissions from forestry and land-use change. If fire episodes such as those that occurred in the tropics of the Americas and around the world become the norm due to warmer and drier conditions, then an increase in C emissions may represent a significant positive feedback to global climate change.

This paper introduces part of the work under international cooperative projects in fire science research. In Brazil, the Fire and Environmental Research Applications Team (FERA) of the US Forest Service, the University of Washington, and Brazil's Instituto Nacional de Pesquisas Espaciais and the Universidade Estadual de Sao Paulo cooperates in several fire sciences research since 1997. Results are presented from projects on flammability assessment of primary, logged and fragmented tropical evergreen forest, prediction of biomass consumption and assessing smoke emissions from fires in tropical ecosystems, and development of a thermodynamic model of flaming, smoldering, and residual combustion.

The presentation will also introduce the results of a cooperation between FERA's Team, the University of Washington, the Fondo Mexicano Para la Conservacion de la Naturaleza, and the Universidad de Guadalajara. The joint research's objectives is supporting Mexico's efforts to develop tools that will allow fire managers of Mexico's natural protected areas and biosphere reserves to anticipate and reduce the threat of damaging wildfires, as well as using fire to restore the ecosystem health where needed. The cooperation concentrates in three Mexican protected areas: the Reserva de la Biosfera "Sierra de Manatlan" in the state of Jalisco, Region "Sierra de Arteaga" in the state of Coahuila, and Reserva de la Biospfera "Selva El Ocote" in Chiapas.

Introduction

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. In addition, a steady increase of wildfire risk has been detected in the last couple of decades in temperate and tropical ecosystems of the world. 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 are tropical ecosystems to wildfires and that the immediate effects can be felt across borders. Occurrence of extreme fire seasons in these two countries, and elsewhere, exceeded the national capacity to solve the problem without external assistance. 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). . These severe and extensive wildfires are also a threat to natural protected areas that have been established to preserve biodiversity and populations of rare, threatened and endangered species, and unique plant communities. 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.

The Fire and Environmental Research Team of the the USDA Forest Service is engaged in cooperation 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 cooperation projects are sponsored by the USDA International Programs and partially funded by USAID. The FERA team has accumulated over 25 years of experience investigating fuels, fire effects, combustion, and smoke emissions from the boreal forests in Alaska, coterminous United States, to the tropical savannas and evergreen forests in Mexico and Brazil. This paper presents results of two international cooperative projects in fire science research.

In Brazil, the FERA Team of the US Forest Service, the University of Washington, and Brazil's Instituto Nacional de Pesquisas Espaciais and the Universidade Estadual de Sao Paulo cooperates in several fire science research since 1997. Cooperation includes 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. The paper introduces the results of a cooperation between FERA's Team, the University of Washington, the Fondo Mexicano Para la Conservacion de la Naturaleza, and the Universidad de Guadalajara. The joint research's objectives is supporting Mexico's efforts to develop tools that will allow fire managers of Mexico's natural protected areas and biosphere reserves to anticipate and reduce the threat of damaging wildfires, as well as using fire to restore the ecosystem health where needed. The cooperation concentrates in three Mexican protected areas: the Reserva de la Biosfera "Sierra de Manatlan" in the state of Jalisco, Region "Sierra de Arteaga" in the state of Coahuila, and Reserva de la Biosfera "Selva El Ocote" in Chiapas.

Fire Management in Protected Areas

Population in Mexico and Brazil has a very high growth rate that exceeds 2% per year (WRI 1966). In the last five decades, a large proportion of their mature humid rain forests has been lost, and at deforestation continues at high rates. Many rivers are polluted, and many parts of the country suffer from water shortages and its consequences such as electricity shortage. Immense areas show environmental degradation and biological impoverishment. In addition, income distribution among the population is remarkably polarized, with more than half of the population living at the poverty level. However, it is striking that these two countries are among of the most biologically diverse in the world (Ramamoorthy et al. 1993). They have a wealth of raw natural resources such as oil, timber, rangeland, minerals, and many other products. These nations have adopted strategies to establish national parks, wildlife refuges, protected areas, marine sanctuaries, world heritage sites, botanical and zoological gardens, and biosphere reserves. Mexico currently counts with 128 federal protected areas that cover approximately 8.7% of the country.

Protecting the country's natural resources is challenging within the social, economic, biological, and cultural context. However, it is critical to understand the role of fire in the ecosystems of the natural protected areas in order to design coherent strategies for conservation, restoration, and sustainability. The role of fire in natural resources and people's attitude toward it has changed over the centuries in the two countries. The perception that fire is bad, which has dominated Mexico's and Brazil's fire policies, is changing as well. There is more public and government awareness that fire is an element of forest and range ecosystems. There is an increasing need of designing more ecological fire management system adequate to the national unique characteristics. Extensive fire research is under way in Mexico and Brazil to develop fire management models that consider the environmental heterogeneity, diversity of the fire regimes and vegetation response, and the need to manage vegetation to sustain a human population that depends on these resources.

An approach that is a model in Natural Protected Areas in Mexico includes the participation in collaborative projects of many national and international institutions. For instance, the Biosphere Reserva "Sierra de Manantlan" in Mexico collaborates in fire projects with federal, state, NGOs, and international institutions (SEMARNAT, CONANP, CONAFOR, FMCN, US-AID, USDA Forest Service, University of Washington, TNC, ENDESU, INIFAP, the University of Guadalajara, and others).

Deforestation, Landscape Fragmentation, Logging and Fire Hazard in Tropical Forests

Over the last 30 years, the world's science community has focused in Brazil because of the global impact of deforestation, landscape fragmentation, fire vulnerability, and smoke emissions. Brazil experienced a high rate of deforestation in the 70s, however, current estimates provided by Brazil's Instituto Nacional de Pesquisas Espacias (INPE) (INPE 2002; INPE 2003) signal that it is 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. 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 cycle. 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).

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.

FERA and Brazilian collaborators from UNESP and INPE have conducted a series of studiesin small experimental burns since 1997 to study biomass combustion and carbon release rates from deforested Amazon forest near Alta Floresta in the state of Mato Grosso. In the course of the experiment, we monitor fuel moisture drying rates, microclimate, regional weather, and changes in canopy closure along a transect from the deforested patch into the forest during the entire dry season from the time of 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 penetration in the undisturbed forest on the edge of land clearing. The objective is to identify the conditions necessary to self-sustain fire spread in closed-canopy forests in the Amazon forest. 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.

These recently created interfaces suffer drastic microclimate changes soon after the logging. Difference between the edge and inside the forest becomes sharper by the end of the dry season. Air temperature at 50-meters inside the forest can be 10 degrees C lower than the edge and relative humidity can be 30% higher inside the forest. Leaf area index also decreases seasonally but is more evident near the edges. These conditions are reflected in litter moisture as well. Fires can penetrate from few meters to over 100 meters inside the forest in these recently created interfaces. During extreme dry years we have observed fires in the region that escape from grassland fires and propagate in the understory for several kilometers 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. Current fire behavior prediction models have trouble to forecast flame spread under very limiting conditions. The average flame front rate-of-spread measured in experiments in Alta Floresta, Brazil varied between 0.16 and 0.26 $m.min^{-1}$. The maximum measured rate of spread was 0.35 $m.min^{-1}$ and the second highest was 0.33 $m.min^{-1}$. We have measured fire propagation with litter moisture content as high as 13.5 %. However, no fire propagation occurred in litter with moisture contents higher than 15 %. The observed flame dimensions were also smaller, maximum length reached 30 cm and width on the order of 10 cm. The flames, with the exception of only one case, were always tilted towards the burned area, due to convection effects and absence of winds. Crown fires are extremely rare in tropical forests, torching only occurs when flames reach tree species that allow crowning. However, crowning is common in some trees on the edges of the border of burned areas. This occurs partially due to the intense heating by the land clearing fire and the creation of ladder fuel effect on the interface.

Poorly known, and probably variable by region, are 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. However, 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 are similar to carbon deposited during the Holocene drought. It is likely that those fires occurred during extremely dry years, and global climate change predicted for the future may increase the recurrence of those extreme climate conditions. Although fires in the tropical ecosystems have been scarcely studied, several studies are under way to identify the conditions that make the forest flammable, allow it 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 (Alvarado et al. 2000).

We have learned from our field studies in eastern Para, Brazil, the 1998/99 season at the FLONA Tapajos, and from the literature, that evergreen forests in the Amazon region become flammable only after periods of a few weeks without precipitation, allowing the surface fuels to dry out enough to carry fire (Alvarado et al. 2000). Trees in temperate forests have developed fire resistance features, however, trees in tropical forests do not have those features. Thus, 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 subregions 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.

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 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.

Harvest of moist tropical forests inevitably increases the risk of destructive forest fires. 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). Increased fire risk associated with climate change and timber exploitation either at the ecotonal areas or in interior Amazon forests has not been previously assessed. Our experience from the state of Para is that partial harvesting has the effect of hastening the flammability of the surface fuels and the drying rate of the woody debris that control fire severity (Alvarado et al. 2000). However, traditional selective logged forest becomes more flammable and reaches dangerous levels faster than forest under a low-impact harvesting regime during the drought season.

Biomass Combustion, Smoke Emissions and Transport

An accurate accounting of smoke emissions and greenhouse gases requires of being able to predict biomass consumption in flaming, smoldering, and residual combustion Most of smoke emission assessments are based on aerial or remote sensing measurements (Andrae 1991). Little ground validation has been done on those assessments, especially in the tropics. Our intensive field studies on biomass consumption and carbon release rates during the process of forest clearing by fire in five test plots varied from 19.5% to 61.5% (Andrade and others 2002). The wide range of biomass combustion is due partly to the forest type, and more importantly, to the effect of different curing periods and of increasing the deforested area surrounding the plots. The consumption, for areas cut and burned during the same year, tended toward a value of nearly 50% when presented as a function of the total area burned. The aboveground biomass of the test site and the amount of carbon before the fire were 496 Mg ha^{-1} and 138 Mg ha^{-1}, respectively. Considering that the biomass that remains unburned keeps about the same average carbon content of fresh biomass, which is supported by the fact that the unburned material consists mainly of large logs, and considering the value of 50% for consumption, the amount of carbon released to the atmosphere as gases was 69 Mg ha^{-1}. The amounts of CO_2 and CO released to the atmosphere by the burning process were then estimated as 228 Mg ha^{-1} and 15.9 Mg ha^{-1}, respectively.

Replication of such an intensive study is almost impossible. Thus, when regional or global assessments of smoke emissions are needed, estimations from Alta Floresta can be extrapolated to relatively similar regions in the tropical world. For instance, Cairns and others (1988) used the data obtained from Alta Floresta to evaluate carbon emissions from spring 1988 fires in tropical Mexico. The authors used used NOAA-AVHRR satellite imagery, biomass density maps, fuel consumption estimates, and a carbon emission factor to estimate the total carbon (C) emissions from the spring 1998 fires in tropical Mexico. All eight states in southeast Mexico were affected by the wildfires, although the activity was concentrated near the common border of Oaxaca, Chiapas, and Veracruz. The fires burned approximately 482,000 ha and the land use/land cover classes most extensively impacted were the tall/medium *selvas* (tropical evergreen forests), open/fragmented forests, and perturbed areas. The total prompt emissions were 4.6 TgC during the two-month period of our study, contributing an additional 24% to the region's average annual net C emissions from forestry and land-use change. Mexico in 1998 experienced its driest spring since 1941, setting the stage for the widespread burning. If fire episodes such as the one that occurred in Mexico and around the world become the norm due to warmer and drier conditions, then an increase in C emissions may represent a significant positive feedback to global climate change.

Transport of smoke emissions across internatinal borders is a concern, especially from the country receiving the smoke. During the fires of 1988 in Mexico and Central America, smoke plumes traveled toward the United States and caused health concerns and warnings in the southern states. Again, intensive studies like Alta Floresta's are helping to understand smoke trajectories in South America. Trosnikov and others (2002) useed a coupled numerical transport-Eta Mesoscale model for evaluating of the transport of CO_2 from a 9 ha slashed Terra Firme Amazonian forest that was burned on August 31, 1998 in the region of Alta Floresta, MT, with an emission of 2052 Mg CO_2 during 144 min. The path of the resulting CO_2 plume was computed for 78 hours, and reached the coast of Santa Catarina as a compact mass. Its concentration, following the wind, was modified by mesoscale diffusion, with values that agreed well with the ones obtained through Taylor's similarity theory.

Climate, People and Fires in Mexican Coniferous Forests

The results described here were published recently by Heyerdahl and Alvarado (2002). Although the study was conducted in the Sierra Madre Occidental, the principles and findings are applicable to other coniferous forests in Mexico. The objective of that work was to study the relation between climate, fire, man, and forest in a forestry setting where fire suppression is less relaxed than the existing in the United States.

The rugged mountains of the Sierra Madre Occidental, in north central Mexico, support a mosaic of diverse ecosystems. On a relatively transversal short transect of only a couple of hundred kilometers, there exists from the tropical forests on Mexico's western coast, to temperate coniferous forests on the high elevations, to the arid lands of the Chihuahuan and Sonoran deserts. Of these, the high-elevation, temperate pine-oak forests are ecologically significant for their extensiveness, biodiversity, and for sustaining the economy of many rural communities living in those forests. They cover nearly half the land area in the states of Durango and Chihuahua (42%), and comprise a similar percentage of the temperate coniferous forest in Mexico as a whole (45%; World Forest Institute 1994; SARH 1994). These forests are globally significant centers of vascular plant diversity, and of endemism in both plant and animal species (Bye 1993; Manuel-Toledo and Jesús-Ordóñez 1993). For example, they have the highest number of pine and oak species in the world and contain many of Mexico's *Pinus*, *Quercus* and *Arbutus* species (33%, 30% and 66%, respectively; Bye 1995). Surface fires were historically frequent in these forests and variations in their frequency may have contributed to the maintenance of this biodiversity

The purpose was to infer the drivers of temporal variation in fire regimes in pine-oak forests of the Sierra Madre Occidental in north central Mexico. A multicentury fire history (1772-1994) was reconstructed of the occurrence of surface fires from 1,469 fire scars on 180 trees sampled at 8 sites over a transect of 700 km in the states of Durango and Chihuahua. Fire intervals were similar among the sites, with Weibull median fire intervals of 3 to 6 years. Most fires probably burned in the warm, dry spring, based on the intra-ring position of fire scars and the seasonality of precipitation, lightning and modern fires in this region. However, some fall or winter fires may have occurred. Annual variation in precipitation and El Niño/Southern Oscillation were strong drivers of current year's fire, probably through their effects on fuel moisture. Extensive fires generally burned during dry years but not during wet ones. Extensive fires also typically burned during La Niña years, which tend to have dry winters in this region. Climate in prior years was also a strong driver of fire, through its effect on fuel loadings. Widespread fires often burned following one to two wet years and also following El Niño years, which tend to have wet winters in this region. Likewise, fires were not widespread following dry years and following La Niña years. Prior year's climate probably affected the growth of grass and herbaceous fuel. Changes in land use, rather than climate, probably caused the near cessation of fire that we reconstructed at some sites because these shifts did not occur synchronously (some ≈1900, some ≈1950). Frequent surface fires continued to burn until the time of sampling at two of our sites.

The recent abrupt cessation of surface fires along the Sierra Madre Occidental likely resulted from a complex mix of local changes in land use, rather than regional variation in climate, because fires did not cease synchronously at all sites. Fire at individual sites can be dramatically impacted by grazing, fire use or suppression, timber harvesting and the construction of roads and railways. We lacked local land-use histories for our sites, but speculate that the differences in timing of fire exclusion among them probably resulted from differences in the type and timing of changes in land use. Mid-twentieth century changes in Mexican land tenure probably resulted in local increases in human occupation of the high elevation pine-oak forests at some of the study sites. There is little quantitative information on human use of the remote and rugged Sierra Madre Occidental before the twentieth century. However, before 1900, these mountains were sparsely populated by indigenous people, such as the Tarahumara, Tepehuano, Mayo, and Yaqui, who occupied the lower valleys and deep canyons in winter and the upper mountains in summer. They practiced slash and burn agriculture and used fire for hunting and religious purposes. The Mexico's Land Reform in the 30's legalized the ejido system and relocated near a million of landless people into these newly created ejidos. Many ejidos were located in the mountain forests of Northern Mexico. The distribution of ejido lands brought a wave of people from low-elevation agricultural areas to settle the forested mountains, resulting in a change from traditional land-use. Today, all but one of the study sites are owned by ejidos. We also especulate that the abrupt cessation of fire at some of these forests in the late 1800s may have been caused by a dramatic increase in travel routes, decades before the major distribution of ejido lands. These roads may have allowed access to parts of the Sierra Madre Occidental, resulting in changes in land use that affected fire regimes. For example, silver mines that resulted in timber harvesting, leading to a decrease in surface fires. We believe that that frequent surface fires continued to burn into the late 1990s in some other stands because they were relatively inaccessible and ignition of fires remained frequent. Some of these remote stands were likely poor sites for grazing or a difficult area for road building and timber harvesting.

Literature

Andreae, M.O. 1991. Biomass burning: its history, use, and distribution and its impact on environmental quality and global climate. Pages 3-21 *in* J.S. Levine (ed.) Global biomass burning, atmospheric, climatic, and biospheric implications. The MIT Press, Cambridge, MA.

Alvarado, E.; Sandberg, D. V.; Higuchi, N.; Toledo, L; Zweede, J. 2000. Fire risk assessment in low impact harvesting at the Floresta Nacional de Tapajos, Para. In. LBA First Scientific Conference. Belem, Para. June 26-30, 2000. Pag. 217.

Bye, R. 1993. The role of humans in the diversification of plants in Mexico. In *Biological diversity of Mexico: Origins and distribution*, eds. T.P. Ramamoorthy, R. Bye, A. Lot, J. Fa, pp. 707-731. New York: Oxford University Press.

Cairns, M.; A.; Hao, W. M.; Alvarado E.; and Haggerty, P. K. 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, João A., Jr. ; Costa, Fernando S. ; Gurgel Veras, Carlos A. ; Sandberg, David V. ; Alvarado, Ernesto C. ; Gielow, Ralf ; Serra, Aguinaldo M., Jr. ; Santos, José C. 2001. Biomass fire consumption and carbon release rates of rainforest-clearing experiments conducted in northern Mato Grosso, Brazil. J. Geophys. Res. Vol. 106 , No. D16 , p. 17,877-17,888

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

Heyerdahl, E.; Alvarado, E.. 2002 . The Influence of Climate and Land Use on Historical Surface Fires in Pine-Oak Forests, Sierra Madre Occidental, Mexico. In. Veblen, T. T.; Montenegro, G.; Swetnam, T. W. (Eds.) Fire and Climatic Change in Temperate Ecosystems of the Western Americas. Series: Ecological Studies. Volume. 160. Springer.

INPE. 2003. Preliminary data on deforestation for 2001-2003 in the Brazilian Amazon forest. Data available at 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.

Negreieros, G.H.; Nepstad, D.; Sandberg, D.; Alvarado, E.; Hinckley, T.; Pereira, M. 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, and 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.; Moreira, A. G., and Alencar, A. A. 1999. Flames in the Rain Forest: Origins, impacts and alternatives to Amazonian Fire. The Pilot Program to Conserve the Brazilian Rain Forest. 190 p.

Ramamoorthy, T. P.; Bye, R.; Lot, A.; Fa, J. 1993. Biological Diversity of Mexico: Origins and Distribution (Oxford University Press, New York), 812 pp.

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

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

Secretaría de Agricultura y Recursos Hidráulicos (SARH). 1994. *Memoria nacional del inventario nacional forestal periodico 1992-1994*. Subsecretaria Forestal y de Fauna Silvestre. Secretaria de Agricultura y Recursos Hidraulicos. Mexico, D. F.

Toledo, V. M.; Ordóñez, M. de. J. 1993. The biodiversity scenario of Mexico: A review of terrestrial habitats. In *Biological diversity of Mexico: Origins and distribution*, eds. T.P. Ramamoorthy, R. Bye, A. Lot, J. Fa, pp. 757-777. New York: Oxford University Press.

Trosnikov, I.; Gielow, R.; Andrade de Carvalho Jr. J.; Gurgel Veras, C. A.; Alvarado, E.; Sandberg, D. V.; José Carlos dos Santos. 2002. Modelling of the atmospheric transport of species emmited by controlled burnings in Amazonia. In. LBA Second Scientific Conference. Manaus.

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

World Resources Institute (WRI). 1996. A Guide to the Global Environment: the Urban Environment. Oxford University Press, New York.

World Forest Institute. 1994. *Mexico: forestry and the wood products industry.* Second edition. Portland, OR: World Forest Institute.