Spreading like Wildfire

tropical forest fires in Latin America and the Caribbean

prevention, assessment and early warning

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Mark A. Cochrane PhD

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DEWA - LAC Support Team:
Kaveh Zahedi and Kakuko Nagatani-Yoshida
Edited & designed by Sylvia Howe

For further information and details of how to obtain copies of this publication please contact:

Division of Early Warning and Assessment (DEWA)
United Nations Environment Programme
Regional Office for Latin America and the Caribbean
Boulevard de los Virreyes 155, Colonia Lomas Virreyes
CP 11000, Mexico, D.F., Mexico
Tel.: (52) 55 52 02 4841 / Fax.: (52) 55 52 02 0950
E-mail: dewalac@rolac.unep.mx
Website: www.rolac.unep.mx/dewalac/eng

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Executive Summary

Until recently, fires in tropical evergreen forests were considered to be either impossible or unimportant, and as a result any effect on people and ecosystems was thought insignificant. The extensive forest fires seen in the late 1990s, not only in Latin America and the Caribbean, but also in the rest of the world, took the issue off the back burner and brought fire to the world's attention.

People became concerned not only with the disappearance of the forest, but also the extensive and widespread human consequences of fires such as their impacts on human health and the economy. Concern about tropical forests now extends beyond deforestation to include the widespread consequences of forest fires, including impacts on human health and the economy.

This document provides an overview of the forest fire situation in Latin America and the Caribbean and the impact that fires have had on the region and its population over the past few years. It also covers the causes, effects and implications of fires and links these to fire managements tools available to policy-makers.

Forests cover 47 per cent of Latin America and the Caribbean, with the vast majority being tropical (95 per cent). Between 1980 and 1990 the region lost roughly 61 million hectares of forest, six per cent of the total forested area. This loss continues. Between 1990 and 1995, a total of 5.8 million hectares per year were lost, another three per cent of the region's remaining forest area. The highest rates of deforestation occurred in Central America (2.1 per cent per year); but Bolivia, Ecuador, Paraguay and Venezuela all had deforestation rates of over one per cent per year between 1990 and 1995. Brazil alone lost 15 million hectares of forest between 1988 and 1997. The extent and importance of the remaining forested areas in Latin America and the Caribbean, both for the region and the world, mean that their forest fire problems need urgently to be addressed.

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Causes

The causes of forest fires are many, mostly linked to direct and indirect human impacts. Forest fires happen as a result of:

- new forest clearence;
- pasture and land maintenance;
- logging and hunting;
- fragmentation;
- previous fires;
- rubbish, cooking or waste burning;
- arson, and
- accidents.

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Within the tropics, landscape fragmentation and land cover change combine to expose more of the forest to fire and consequently raise the risk of fires across the entire landscape. Ignition sources continue to grow and a forest fire is more likely to start. Fires in the tropics are increasing in severity and frequency.

Change in the frequency, intensity and pattern of forest fires in the tropics is a new phenomenon. If fire incidence stays at current levels or increases in frequency, then many rain forests will be replaced with vegetation that is less diverse and more fire-tolerant.

Worse each year

The widespread fires of 1998 changed the landscape of Latin America's tropical evergreen forests by damaging vast forested areas adjacent to fire-maintained human ecosystems.

The fires are therefore likely to become increasingly severe each year, a fact that is not yet appreciated by the resident populations, policy makers, fire managers or most scientists.

Forest fires have not only resulted in dramatic loss of forests, but have also seriously affected human health, economy and the environment.

Degraded forests in tropical Latin America are increasingly prevalent, and so therefore is the associated fire problem. In Central America, over 2.5 million hectares of land were affected by fire in 1998. In Nicaragua, Guatemala and

Honduras 900 000, 650 000, and 575 000 hectares were affected respectively. In Mexico an additional 850 000 hectares burned.

The situation has been just as severe in South America. In Bolivia, wildfires had an impact on more than 3 million hectares of land. Recent fires have burned through tropical forests in Brazil, Colombia, Venezuela, Guyana and Suriname. More than 5 million hectares have been badly burned in the Brazilian state of Roraima.

Effects on people

Smoke from fire causes thousands of respiratory, cardiovascular and eye problems. In addition to numerous cases of constrictive lung disorder and obstructive lung disorder, the number of cases of asthma, pneumonia, bronchitis, acute laryngitis, bronchiectasis and conjunctivitis rise dramatically. The extent of the damage to human health from smoke inhalation depends on the constituents of the smoke, its concentration, and the total exposure time.

It also can kill: in 1998, 70 Mexican firefighters were killed, and there were 700 smoke-related deaths in the Brazilian Amazon.

Economic costs

The true economic costs of tropical forest fires are largely unknown. This is due, in part, to a lack of data or analysis, but it is also a result of the complications of working out cause and effect. Negative political implications also discourage full disclosure.

Economic implications of uncontrolled fires include everything from medical costs and airport closures to timber and erosion losses. The effects of fires need not be confined to one area, but can and do affect the health and economies of others. These external costs of fire (lost work days, production slow-downs, lost tourism dollars) are unlikely to show up in the accounting of the region or nation that is responsible. Furthermore, the links between a fire and its effects may be both obscure and delayed. The economic damage assessments that do exist are likely to be conservative. In the case of Roraima, Brazil, the cost of damages from the expected carbon release (42 TgC) alone are estimated at US$ 840 000 000. Across Latin America, a minimum of 9.2 million hectares were affected by wildfires in 1998. The resulting damage can be crudely estimated to have reached $10 000 to $15 000 million.

Environmental impacts

The environmental impacts from tropical forest fires range from local to global. Local impacts include soil degradation, increased risks of flooding and drought, reduced abundance of animals and plants, and increased risk of recurrent fires. Global effects of these fires include the release of large amounts of various greenhouse gasses, reduced rainfall and increased dry lightning as well as contributing to the reduction of biodiversity as well as contributing to the extinction of populations or species.

In Latin America, millions of hectares of damaged tropical forests still cover the landscape. These damaged forests will release carbon to the atmosphere, erosion will increase, water retention and biodiversity decrease, and future fires are likely to be more frequent.

Policies against forest fires

There is a need for many more policies and tools in the region to prevent, monitor and fight fires. These can be broken down into fire prevention, fire management, fire prediction, fire detection and monitoring and fire fighting.

1 The importance of fire prevention in any fire management strategy can not be over-emphasised. Prevention is less expensive than suppression and has the added benefit of reducing the costs of fire damage.

- Campaigns need to be tailored to individual cultures and communities.
- Zoning of land use across tropical landscapes can be effective.
- It is necessary to create and maintain an accurate database of fires that have occurred in order to judge the effectiveness of a fire-prevention management programme.
- Prevention and education have to lead any fire management programme in the tropics.

2 Fire management at national level involves the establishment of the necessary infrastructure, equipment and personnel to be able to predict, detect, monitor and respond to forest fires. Special emphasis needs to be placed on international cooperation in Latin American fire fighting operations, since no single nation has the human, material, or financial resources to cope alone with severe fire situations.

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Interaction between nations and personnel exchange/training programmes should be encouraged and fostered by international agencies.

3 Fire prediction or early warning systems need to integrate information about weather, vegetation dryness, fire detection and fire spread to provide a simple measure of the fire situation. In tropical regions, it is important to know the status and distribution of land cover. Reasonably accurate and current maps of the changing landscape are therefore needed.

4 Patrols, towers and aircraft are integral parts of the fire detection and monitoring process but satellite detection is a necessity. Trade-offs exist for using AVHRR, GOES, DMSP-OLS, SPOT, SAR and LANDSAT 7 satellite platforms for fire detection and monitoring and mapping. New satellite sensors including, MODIS, TRMM, and BIRD will expand capability but aerial detection and suppression of fire in tropical forests can be critical and still problematic. The forest canopy disperses smoke and obscures vision, making it difficult to locate fire lines. It intercepts much of the water and fire suppression agents that are dumped on fires, making them much less effective.

5 Fire fighting should make use of aerial and ground suppression forces. These should be well trained, equipped and coordinated through a well-defined command structure. However, it has been clearly established that fire mitigation efforts based solely on professional fire fighting forces and punitive legislation will fail. Local populations must be involved in and supportive of efforts against fire. National fire programmes in developing countries have not been as effective as they could have been due to lack of availability of fire-fighting equipment and its high cost. Local production should be encouraged.

Fire-prone regions should have the necessary fire fighting materials ready and waiting, so that they can respond to fire events rapidly and effectively. Speed of response is critical in tropical forests. They need to be able to predict when and where fires are likely to occur. Mopping-up operations to prevent fires starting up again in tropical forests are particularly necessary and time-consuming. Falling foliage from trees killed in a fire can begin to blanket the ground with a new fuel layer within a few days. This process has resulted in as many as three fires in a single area within a given year. To prevent this, a detailed search of the entire affected area is necessary to extinguish anything still smouldering. If a fire is rapidly contained, the mopping-up operation will be minimal, but if it is allowed to burn over substantial areas of tropical evergreen forest, time and manpower needed to deal with this increases substantially.

Many different strategies can be adopted to tackle the fire problem, from better education and fire management to economic incentives and land use planning. But, these will not be successful without the support and involvement of local people. At present they are indifferent or resigned to the problem of fire, and fire management plans must work to change this attitude so as to encourage and empower proactive fire prevention.

Introduction

Latin America and the Caribbean covers an extensive area with many ecosystems, cultures, economies and governments, each with its own fire management problems. The situation in each country, like the people, is different; but also, like the people, there are many similarities. This document does not try to cover the fire management situation in all ecosystems. It concentrates on the current fire conditions and management in tropical evergreen forests.

Fires in temperate forests and savanna are serious, but these ecosystems are adapted to fire to varying degrees and the interplay between fire and vegetation within them is reasonably well understood. Fires in tropical evergreen forests, however, were, until recently, considered not to happen or to have negligible effects.

For several years now, people across the world have been exposed to images of deforestation in tropical forests. The scenes of slash-and-burn agriculture and pasture creation have made these land uses synonymous with fire in the tropics for many people. Lost in the smoke and haze of these annual burnings has been the growing effect that escaped fires are having on standing forests that were not intended to be sacrificed. In recent years, the growth of selective logging for the tropical timber trade has exacerbated the problem by turning large tracts of densely-vegetated, humid, fire resistant forest into highly combustible, fuel-laden tinderboxes. The potential for disastrous forest fires to occur in a landscape mosaic of fire vulnerable forests and fire dependent agriculture was clearly illustrated by Indonesia's great fires of 1982-1983. However, in 1997 and 1998, when fires burned again in Indonesia, they also burned throughout Southeast Asia, Africa, Central and South America, illuminating the potential for fires in tropical evergreen forests.

Though the great fires have occurred during the extensive droughts of *El Niño* years, fires in tropical forests have not been limited to these years alone, and they certainly won't be in the future. Research over the last several years has shown not only the susceptibility of logged, and even undisturbed forests to fire, but also has uncovered the threat these fires pose, changing these lushly diverse rain forests into biotically-impoverished scrublands. The implications of these and other research findings are provided in this document.

Much current tropical fire research has been conducted in Brazil's Amazon, so there is an emphasis on this area in this document. This should not be taken to indicate that other countries do not have similar or even worse fire problems. All tropical evergreen forests of Latin America near human settlement are affected.

Fire has played little or no evolutionary role in tropical evergreen forests, so the current fire situation in these forests is a matter for concern. Fires here are no different to fires anywhere else in the world but the ecology of these forests makes the effects of fires disproportionately severe.

Fire managers need to understand this. A lot of knowledge has been gained in combating fires in temperate forests and other ecosystems around the world, but the

Latin-American tropics are different, and the lessons learned from fighting fires elsewhere may not apply. This document provides insight into both the cultural and ecological hurdles fire managers need to jump in these regions, as well as describing the tools that they have at their disposal.

It will not be easy to reconcile fire-dependent populations with fire-averse ecosystems, but this must be done, or forests will continue to be degraded. And as they go, so will the people who live in or near them.

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What? Where? Why?

Fire on Earth is as old as the hills. Or the forests. Fire has been part of the Earth's processes for as long as fuel, oxygen and heat have existed together. If they are present in large enough quantities, fire happens. If they aren't, it doesn't. At its most basic, therefore, any discussion of fire probability, fire behaviour or fire fighting can be reduced to the conjunction and interaction of fuel, oxygen and heat. Ecosystem composition, structure and function are therefore directly tied to and sometimes controlled by fire disturbance.

Natural Fire

Wildfires have been a common occurrence while terrestrial vegetation has been evolving. It has, therefore, had an effect on the evolutionary process. Fire still wipes out species that cannot not survive or propagate in the presence of periodic fire disturbance.

If fires are rare but intense, then species that can resprout or germinate immediately afterwards will be better able to survive. If they are very frequent but of low intensity, fire-resistant species, and others which can fulfill their life cycles between fire occurrences, will be favoured over longer-lived non-fire-resistant species.

For millions of years lightning-induced fires have forced vegetation to adapt to local conditions. Depending on the climate and local fuel structures, the resultant wildfires affect small or large areas, are common or rare, of low or high intensity. The end result is called the natural fire regime, which applies to the pattern of fires characteristic of a region or ecosystem.

Since fire regimes are comprised of the combined effects of fire type, intensity, pattern and frequency (Mutch *et al*. 1999), changing any of these factors will obviously change a region's fire regime. Climate has been the overriding determinant of fire occurrence for much of evolution, but, ever since man domesticated fire, many fire regimes and hence ecosystems have become anthropogenically driven.

The most favourable conditions for fire

Drought, in the context of the causes of fire, is analogous to heat, since the main effect of water is to increase the heat requirements for sustained combustion to be achieved. Therefore, as oxygen is ubiquitous in the atmosphere, fire managers can assess fire ignition risk and severity if they can predict the weather and fuel conditions in an area.

If weather conditions are dry and hot, especially over an extended period, there will be more fuels available across the landscape. These are substances that require less heat to reach the point of combustion than is being radiated by the surrounding environment. Sustained combustion occurs when burning spreads into adjacent fuels to start combustion before the currently-burning fuels are consumed. If this continues, then the fire will spread.

Fire behaviour is the result of weather conditions, fuel composition and structure and topography.

- Both heat and dryness serve to reduce the necessary amount of heat to cause ignition.

- Wind aerates a fire and increases oxygen availability, enhancing the rate and intensity of the combustion process increase and fire spread.

- Fuel moisture and chemical composition affect the temperature of ignition and also the energy release from combustion.

- Fuel structure dictates the availability of oxygen and effectiveness of heat transfer.

- Topography affects the relative geometry of a fire's flames and nearby fuels, thereby affecting the efficiency of heat transfer from the fire to adjacent fuels, and hence, the likelihood and rate of fire spread.

Fire Regions

South America

Nearly half the South American continent is covered in forests, and another 11 per cent is covered by various other woodlands. The continent spans a vast area from the coastal forests on the Caribbean to the temperate rain forests *(Nothofagus* spp.) of *Tierra del Fuego*. Regional vegetation varies from being nearly non-existent in the Atacama desert to being lushly profuse within the wetter parts of the Amazonian rain forest. The forest cover of individual countries varies from 90-95 per cent in Guyana, French Guyana and Suriname to less than five per cent in prairie-dominated Uruguay. Temperate forests are located primarily within Argentina, Chile, Paraguay and southern Brazil, covering 11 per cent of these regions but these forests make up only five per cent of the continent's total forest cover. Most of the other 95 per cent of the continent's forests are tropical rain forests, the majority in the expansive Amazon Basin. Deforestation rates in South America are approximately 0.6 per cent per year with most forest clearance occurring in the tropical forests. Forests data by individual country are presented in Table 1.

Tropical forests make up 95 per cent of the forest cover in South America (FAO 1999). Though substantial amounts of tropical evergreen forests are located in Bolivia, Peru, Colombia, Venezuela, Ecuador, French Guiana and Guyana, the vast majority of these forests are in Brazil. Both Bolivia and Brazil have significant export markets for tropical timber. In addition, the Brazilian Amazon exports large amounts of tropical timber to the south of Brazil for domestic consumption.

Fire affects rain forests throughout South America to differing degrees. Effects are more pronounced in regions with extended dry seasons, selective logging and large populations. Recent fires in the region include more than 7 000 forest fires in Colombia in 1997 (Brown 1998), intense fires in forest concessions and agricultural lands in Bolivia in 1993 and 1994 (Mostacedo *et al*. 1999), and 1999 (Musse 1999), and numerous fires across the Guyana Shield including Brazil, Colombia, Venezuela, Suriname and Guyana in 1998 (Grégoire *et al*. 1998). Additional forest fires have been reported from forests throughout southern, central and eastern Amazonia in Brazil from 1985 to 1997 (Uhl and Bushbacher 1985; Kauffman 1991; Cochrane and Schulze 1998; Stone and Lefebvre 1998; Peres 1999; Cochrane *et*

Table 1. Forest amounts and cover change in South America.

Forest Cover 1995							
Country/region	Total Forest Thousands of hectares	Woodlands Thousands of hectares	Non-forest Thousands of hectares	Total Forest %	Woodlands %	Non-forest %	Forest Cover Change 1990-1995 %/yr
Argentina	33 942	16 500	223 227	12.4	6.0	81.6	-0.3
Bolivia	48 310	8 632	51 496	44.6	8.0	47.5	-1.2
Brazil	551 139	105 914	188 598	65.2	12.5	22.3	-0.5
Chile	7 892	8 550	58 438	10.5	11.4	78.0	-0.4
Colombia	52 988	9 041	41 841	51.0	8.7	40.3	-0.5
Ecuador	11 137	3 569	12 978	40.2	12.9	46.9	-1.6
French Guiana	7 990	321	504	90.6	3.6	5.7	0.0
Guyana	18 577	331	777	94.4	1.7	3.9	0.0
Paraguay	11 527	6 388	21 815	29.0	16.1	54.9	-2.6
Peru	67 562	16 754	43 684	52.8	13.1	34.1	-0.3
Suriname	14 721	317	562	94.4	2.0	3.6	0.0
Uruguay	814	120	16 547	4.7	0.7	94.7	0.0
Venezuela	43 995	23 493	20 717	49.9	26.6	23.5	-1.1
Temperate South America	42 648	25 170	298 212	11.7	6.9	81.5	-0.3
Tropical South America	827 946	174 760	382 972	59.8	12.6	27.6	-0.6
South America	870 594	199 930	681 184	49.7	11.4	38.9	-0.6

source: FAO 1999

al. 1999). In the Amazonian state of Roraima, between 1 100 000 and 1 400 000ha of undisturbed forest burned in 1998 alone (Barbosa and Fearnside 1999; Shimabukuru *et al*. 2000). Additional rain forests of the Mata Atlantica region of Brazil are also threatened by fire. These forests have been 90 per cent deforested and exist only as fire susceptible fragments. The biodiversity contained in these forest remnants makes their conservation particularly important (Mutch *et al*. 1999). Though not tropical, the *Nothofagus* rain forests of Chile and Argentina, are similarly affected by fire, especially during extreme droughts (Kitzberger 1997) and may respond like tropical evergreen forests to more frequent fire occurrence.

In South America, the majority of temperate forests are in Chile, Argentina, Paraguay and southern Brazil. The major savanna ecosystems of South America include the Colombian and Venezuelan *llanos*, the *llanos Moxos* of Bolivia, and the *cerrados* of Brazil (Cavelier 1998) as well as the grasslands of Argentina and Uruguay. Additional anthropogenically-derived grasslands exist in some regions of Colombia (Aide and Cavelier 1994; Cavelier *et al*. 1998), Venezuela (Rull 1992) and northern Brazil.

For further discussion of fire in temperate forests readers are encouraged to consult excellent references concentrating on these forests, including, Agee (1998),

Table 2. Forest amounts and cover change in Central America and Mexico.

Forest Cover 1995							
Country/region	Total Forest Thousands of hectares	Woodlands Thousands of hectares	Non-forest Thousands of hectares	Total Forest %	Woodlands %	Non-forest %	Forest Cover Change 1990-1995 %/yr
Belize	1 962	119	199	86.1	5.2	8.7	-0.3
Costa Rica	1 248	113	3 745	24.4	2.2	73.3	-3.0
El Salvador	105	763	1 204	5.1	36.8	58.1	-3.3
Guatemala	3 841	5 212	1 790	35.4	48.1	16.5	-2.0
Honduras	4 115	1 446	5 628	36.8	12.9	50.3	-2.3
Mexico	55 387	80 362	55 120	29.0	42.1	28.9	-0.9
Nicaragua	5 560	1 705	4 875	45.8	14.0	40.2	-2.5
Panama	2 800	143	4 500	37.6	1.9	60.5	-2.1
Central America and Mexico	75 018	89 863	77 061	31.0	37.1	31.9	-1.2

source: FAO 1999

Rothermel (1983) and Pyne (1984) among others. Kauffman *et al*. (1994) and Mistry (1998) summarise the characteristics and effects of fire for various savanna *'cerrado'* ecosystems.

Central America and Mexico

Forests comprise 31 per cent and other woodlands make up 37 per cent of the Central America and Mexico region. Deforestation varies from slight in Belize, which is still 86 per cent forested, to extensive in El Salvador, which only has about five per cent forest cover remaining. Mexico contains most of the region's land area (79 per cent) and, despite being only 29 per cent forested, still contains 74 per cent of the region's forests. The region has a broad range of climatic zones, and this has resulted in a wide variety of vegetation and forest types from the semi arid and drier regions, which make up most of Mexico, to the dense tropical forests of Panama's Darien Gap. Forests of the region are a mix of pine and deciduous forests and various types of tropical rain forest. Forest data by individual country are presented in Table 2.

In Central America and Mexico, temperate forests are prevalent at higher altitudes and in drier locations. Most temperate forests and plantations are coniferous, with most species being pines. Among savanna ecosystems most open grasslands in Central America are anthropogenic in origin. Mexico has a large area of natural arid lands.

In Central America and Mexico, tropical forests comprise much of the forest cover from southern Mexico to Panama. Much of the region is subject to fires from forest clearing and the maintenance of pastures. Logging is present throughout the region in varying degrees. Timber is used for sawnwood and household fuel. Much of the timber production is used domestically by each country, but limited exporting does occur.

Forest fires occurred throughout Central America and Mexico during the extreme *El Niño*-spawned drought of 1998. In Central

America the 1998 fires are estimated to have affected 2.5 million hectares with 85 per cent of the total area contained in Nicaragua, Honduras and Guatemala (Mutch *et al*. 1999). In Mexico, 97 per cent of the 1998 fires were attributed directly to illegal logging and slash-and-burn farming by the Environment, Natural Resources and Fisheries Secretariat (SEMARNAP), operating as the Environment and Natural Resources Secretariat (SEMARNAT) since 2001 (Business Mexico 1999). These fires burned an additional 583 664 hectares of forests (Trejo and Pyne 2000). Published country statistics on fire from this region do not distinguish between forest types in the affected areas but all nations have reports of fires in tropical broadleaved forests.

The 1998 season was an extreme fire year and is, therefore, not indicative of typical patterns of fire occurrence. There are, however, reports of fires occurring in tropical forests during non-*El Niño* years in Costa Rica, Belize and Nicaragua (Middleton *et al*. 1997; Kellman and Meave 1997; Jacques de Dixmude *et al*. 2000) so tropical forest fires should not be considered unique to *El Niño*-related drought. In Mexico during 1999, a large fire complex affected at least 35 per cent of the 1.4 million ha Chimalapas cloud forest in Oaxaca and Chiapas states (Ferriss 1999).

The Caribbean

The forests of the Caribbean are roughly 19 per cent of the land area and are dispersed over the region's islands. Other woodlands cover an additional 11 per cent of the region. Substantial amounts of clearing and disturbance have occurred since European occupation. Remaining forest cover varies in density from virtually none on Barbados and the Cayman Islands to more than 61 per cent on Dominica.

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Table 3. Forest amounts and cover change in the Caribbean.

Forest Cover 1995							
Country/region	Total Forest Thousands of hectares	Woodlands Thousands of hectares	Non-forest Thousands of hectares	Total Forest %	Woodlands %	Non-forest %	Forest Cover Change 1990-1995 %/yr
Anguilla	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Antigua and Barbuda	9	16	19	20.5	36.4	43.2	0.0
Barbados	n.a.	5	38	n.a.	11.6	88.4	n.a.
British Virgin Islands	4	2	9	26.7	13.3	60.0	-4.4
Cayman Islands	n.a.	6	20	n.a.	23.1	76.9	n.a.
Commonwealth of the Bahamas	158	0	843	15.8	0.0	84.2	-2.6
Cuba	1 842	1 302	7 838	16.8	11.9	71.4	-1.2
Dominica	46	6	23	61.3	8.0	30.7	0.0
Dominican Republic	1 582	446	2 810	32.7	9.2	58.1	-1.6
Grenada	4	5	25	11.8	14.7	73.5	0.0
Guadaloupe	80	0	89	47.3	0.0	52.7	-1.7
Haiti	21	108	2 627	0.8	3.9	95.3	-3.4
Jamaica	175	399	509	16.2	36.8	47.0	-7.2
Martinique	38	28	40	35.8	26.4	37.7	-1.0
Montserrat	3	1	6	30.0	10.0	60.0	0.0
Netherlands Antilles	n.a.	7	73	n.a.	8.8	91.2	n.a.
Saint Kitts and Nevis	11	11	14	30.6	30.6	38.9	0.0
Saint Lucia	5	29	27	8.2	47.5	44.3	-3.6
Saint Vincent and the Grenadines	11	1	27	28.2	2.6	69.2	0.0
Trinidad and Tobago	161	68	284	31.4	13.3	55.4	-1.5
Turks and Caicos Islands	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
U.S. Territory and other islands	275	12	633	29.9	1.3	68.8	-2.1
Caribbean	4 425	2 452	15 954	19.4	10.7	69.9	-1.7

source: FAO 1999

Rainfall varies substantially throughout the Caribbean and this, in combination with elevation, has resulted in a variety of vegetation cover types—from savanna and arid ecosystems to mixes of temperate forests, montane forests and broadleaved rain forests, often existing in close proximity. The vast majority of the region's forests (77 per cent) are in Cuba and the Dominican Republic. Forest data by individual country are presented in Table 3.

In the Caribbean, there are both temperate and tropical forests scattered among the islands of more than 13 countries and other seven insular territories. Remaining forests are fragmented and often subject to small-scale logging. There do not appear to be any published data or statistics on fire occurrence in these forests and so the fire situation is uncertain. Among savanna ecosystems, the majority of open grasslands in the Caribbean are anthropogenic in origin.

The rest of this document will concentrate on fire in tropical evergreen forests.

Tropical Forest Fire Characteristics and Management Issues

Intact Forest

All tropical forests are not the same. There are many varieties, from the dry tropical forests, formerly characteristic of much of Costa Rica, to the species-rich, flooded rain forests of the Peruvian Amazon to the seasonally-flooded varzea forests of the Brazilian Amazon. The seasons in forests are dependent on where they are and, while some regions experience little or no seasonality, many other regions have one or two extensive dry periods during the year. Response to drought is species-specific; some species become drought-deciduous while others rely on deep roots to access water and maintain an evergreen canopy (Nepstad *et al* 1994).

The vast majority of the tropical forests in Latin America, however, are broadleaved evergreen, upland *terra firme* forests. Relatively stable temperatures and high humidity, maintained by evapotranspiration within the forest canopy, characterise the interiors of these forests.

Tropical humid and tropical moist forests do not generally encourage fires. Despite consistently high temperatures and large amounts of potentially burnable biomass, high humidity keeps the forest fuels too damp to burn.

Intact tropical forests have been considered largely immune to fire (Kauffman and Uhl 1990), with forest burning occurring rarely, if ever. However, studies across the Amazon show the presence of charcoal strata within the soil profile. Though no detailed studies of fire return intervals exist for tropical forests in Latin America, dates of the fires in existing charcoal studies (Sanford *et al*. 1985; Saldarriaga and West 1986; Turcq *et al*. 1998, Hammond and ter Steege 1998) imply fire return intervals of hundreds or even thousands of years (Cochrane *et al*. 1999, Cochrane 2000a,b). Anthropological evidence from some regions of the Amazon has been used to hypothesize that fires may have coincided with mega-*El Niño* events (Meggers 1994). Regardless of the reason for the fires, they must have been insignificant evolutionarily, since the trees in these forests show no specific adaptations to fire (Uhl and Kauffman 1990).

Degraded Forests

Tropical Latin America has its intact forests, but also a growing quantity of degraded ones. These have suffered from varying degrees of direct and indirect human impact. The process of clearing lands for agriculture and cattle ranches fragments the remaining forests and exposes vast areas of the resulting forest edges to greater drought and wind. More trees die and live biomass is reduced for at least 100m into the forest (Laurance *et al*. 1997). Substantially increased rates of mortality for larger trees occur out to 300m (Laurance *et al*. 2000).

Tropical forests within Latin America are being exposed to more and more logging pressures. Logging is often selective as only the more economically-valuable trees are removed, sometimes as few as one or two

high-value species such as mahogany (Veríssimo *et al*. 1995), or it can encompass 100 or more species in more-developed logging regions (Uhl *et al*. 1997). Using traditional felling techniques, the felling of a single tree can directly result in the death of six other nearby trees (Veríssimo *et al*. 1992). Furthermore, logging operations, with the creation of logging roads and skid trails, often lead to as many as 40 per cent of the remaining trees being killed or severely damaged (Uhl *et al*. 1991). The logging industry in the Brazilian Amazon alone is estimated to have had an effect on 1 100 000 – 1 500 000ha of forest in 1996 alone (Nepstad *et al*. 1999).

Fire disturbance is yet another ongoing degradation process in tropical forests. These fires have been reported to be common in logged forests next to cattle pastures (Uhl and Buschbacher 1985) and are directly linked to forest edges and fragmentation (Cochrane, in press). In 1998, fires in Roraima, Brazil impacted over 1 100 000 ha of previously undisturbed forest (Barbosa and Fearnside, 1999). Individual large fires of up to 100 000 ha have been occurring in the Amazon since at least 1988 (Stone and Lefebvre 1998) and have become recurrent in some locations (Cochrane and Schulze 1998, 1999). The end result has been the accumulation of millions of hectares of forests, damaged to various degrees. In some regions, the problem has become so bad that unintentional fires have doubled apparent deforestation rates in some years (Cochrane *et al*. 1999).

Susceptibility to Fire

Fire management in the tropics will require knowledge of when, where and why forests are susceptible to fire. Tropical humid and tropical moist forests are, as their names imply, normally quite wet. Beneath the canopy, high humidity is maintained during even the driest days by evapotranspiration, with most, if not all, the moisture coming directly from the forest trees (Moreira *et al*. 1997). These forests were once thought to be largely immune to fire, but as recent years and soil charcoal studies (Sanford *et al*. 1985; Saldarriaga and West 1986; Turcq *et al*. 1998, Hammond and ter Steege 1998) have shown, these forests can indeed burn.

Selective logging opens the formerly-closed canopy and allows light to penetrate to the forest floor, drying the residual logging debris and increasing the flammability of these forests. As early as 1985 there were warnings that fire was being promoted in the forests of eastern Amazônia by a "disturbing synergism" between cattle ranching and selective logging (Uhl and Buschbacher 1985). Subsequent studies (Uhl and Kauffman 1990, Holdsworth and Uhl 1997, Cochrane and Schulze 1999, Cochrane *et al*.1999) have shown these warnings to be accurate.

Both logging and subcanopy surface fire dramatically change the susceptibility of forests to fire (Uhl and Kauffman 1990; Cochrane and Schulze 1999; Mostacedo *et al*. 1999). Normally, an intact tropical forest can go more than a month without rain and still maintain its resistance to fire (Uhl *et al*. 1988). However, long term droughts may cause even deep-rooting tropical forests to become flammable (Nepstad *et al*. 1999). Selective logging can cause the forest to dry rapidly and become flammable in as

More On Fuels

Fuels are commonly divided into different size classes that have been determined to have specific moisture flux characteristics. Specifically, fuels are frequently divided into 1, 10, 100, and 1 000 hour fuel classes (0-0.62, 0.62-2.54, 2.54-7.62, >7.62 cm). The number reflects the amount of time a fuel particle of a given size requires to reach 63 per cent of equilibrium after a change in ambient moisture conditions (Agee 1993). More basically, this simply means that smaller fuels like 1-hr fuels can either dry or become moist relatively quickly while larger fuels (e.g. 1 000-hour) take a long time to dry but also require a long time to recover moisture.

In the case of many evergreen tropical forests, fire will be carried in what are effectively 1-hr fuels. These fuels, in the form of the litter layer (e.g. fallen leaves), frequently form a continuous coverage on the forest floor. However, in a humid forest these leaves are incapable of maintaining sustained combustion (Uhl *et al*. 1988). If ambient humidity levels drop though, these moist fuels can dry to the point of flammability in just a few hours. If a fire happens at this point, it can spread through the forest because the fuels are dry enough to be 'available' and are also continuous across the forest.

few as six to eight days without rain (Uhl and Kauffman 1990). Once a forest has burned, it is much more susceptible to fire in the future. Studies have shown that while only five per cent of an intact forest (mainly treefall gaps) was susceptible to fire after 16 days without rain, 50 per cent of a previously-burned forest was flammable. Forests which had burned twice were 90 per cent flammable in the same time period (Cochrane and Schulze 1999).

Extensive droughts can make the wettest forest susceptible to fire. Selective logging and forest burning, however, make forests flammable even during common weather events such as a few weeks without rain. Prediction of which forests will burn will require knowledge of current climatic and land cover conditions as well as likely ignition events. Forests which have been logged or previously burned will be much more susceptible to fire and therefore will require greater protection from it.

Fuel Loading

Fire risk is not only a function of a forest being susceptible to burning but also a question of expected fire severity. Fire behaviour is influenced by a complex interplay of wind, weather, topography, fuel content and fuel structure. Critical, though, is the amount of fuel available to burn and how close areas of fuel are to each other on the landscape. No fuel means no fire, no matter how many ignition events occur (e.g. some desert biomes). If available fuels are very patchy on the landscape, without an intervening medium to allow fire movement, fires are unlikely to spread. Most deforestation fires can be considered to be like this since they are kept to a heavy fuel area (slashed forest) and normally

Table 4. Fuel potential present in downed woody debris for several different tropical forest types and conditions.

Fuel Quantities								
Forest type	Litter (Mg/ha)	Root mat (Mg/ha)	1-hr (Mg/ha)	10-hr (Mg/ha)	100-hr (Mg/ha)	1000-hr (Mg/ha)	Total (Mg/ha)	Source
Bana	2.8±0.3	8.2±0.7	0.22±0.04	0.9±0.2	0.5±0.2	0.0±0.0	13±2	1
Caatinga	3.2±0.3	35.8±2.7	0.34±0.03	1.0±0.1	1.6±0.6	2.5±1.6	44±3	1
Second growth	3.8±0.6	17.2±2.4	0.53±0.07	0.8±0.2	0.2±0.2	40.9±18.2	63±15	1
Species-rich Terra Firme	2.4±0.1	48.6±1.9	0.61±0.07	1.7±0.4	3.1±1.2	7.6±4.9	64±20	1
Species-dominant Terra Firme	3.1±0.3	77.9±8.7	0.48±0.03	1.3±0.2	2.0±0.6	23.1±10.3	107±10	1
Low Igapo	8.0±0.6	231±12.4	0.31±0.03	2.1±0.4	1.5±0.6	10.6±6.4	253±15	1
Primary Forest	4.1±0.2	n.a	0.9±0.2	2.6±0.6	5.7±2.5	42.3±19.7	55.6±16.2	2
Logged Forest	6.1±0.3	n.a	3.3±0.6	8.7±2.0	23.4±4.5	137.4±42.0	178.8±41.2	2
Second-growth forest	4.2±0.0	n.a	0.9±0.1	2.7±0.5	1.0±3.3	18.8±9.0	27.7±6.7	2
Unburned Forest	3.0-5.0	n.a	1.3	5.2	16.8	15.5	42.8	3
Once-burned Forest	3.0-5.0	n.a	3.3	11.8	36.8	124.9	180.8	3
Twice-burned Forest	3.0-5.0	n.a	6.6	16.9	40.1	106.1	173.7	3

Source:
1. Amazon Territory, Venezuela (Kauffman *et al.* 1988)
2. Paragominas, Pará, Brazil (Uhl and Kauffman 1990)
3. Tailândia, Pará, Brazil (Cochrane *et al.* 1999)

can't move more than a few metres into the damp forest (Uhl and Buschbacher 1985).

Tropical forests are some of the most biomass-rich ecosystems on Earth. All vegetation biomass is potential fuel and all that protects it is its moisture. The potential for fire ignition and spread exists only when the forest is being dried faster than its transpiration-derived humidity can be replaced.

In most cases, although small fuels may blanket a forest, they form only a thin carpet and therefore can support only a small fire in any one place. The forest floor is usually well-sheltered from air movements so fuel moisture will be the primary determinant of fire spread rates. If larger fuels are encountered by the flames and sufficiently dry to burn they will create larger and longer-lasting fires. In an intact forest, such conditions will be uncommon and so severe fire conditions will be rare and very localised. However, in forests that have been previously disturbed by selective logging (Uhl and Kauffman, 1990), fire (Cochrane *et al*. 1999) or severe winds such as those that occur during hurricanes, fuel amounts can increase dramatically. Table 4 provides typical fuel loads for several forest types and conditions (Kauffman *et al*. 1988; Uhl and Kauffman 1990, Cochrane *et al*. 1999).

Fuel loads in disturbed forests can be three or more times normal levels. Fire risk is much worse, since they not only have greater susceptibility to fire but also greater quantities of combustible fuels. While fires in undisturbed forests are easily dealt with by

A Brazilian Example

Despite colonization of the Amazon by early Brazilians, the fire situation did not change substantially. The indigenous peoples were displaced in many areas, but the colonists practiced a similar form of slash-and-burn agriculture. Most settlements were along rivers and the majority of logging happened adjacent to rivers so that the logs could be easily transported to the mills. Episodic fires did occur, but forest fire was still not considered to be a significant problem.

The fire situation in the Brazilian Amazon changed during the 1960's and 1970's. By building a network of roads linking the Amazon to the rest of the country, Brazil's military government opened up vast tracts of land for colonization and changed the nature of fire in the Amazon. Millions of colonists were settled along the roads to create towns and tame the forest. Land was free for the taking if someone could show that they were both occupying and 'improving' the land. 'Improving' basically implied deforesting land to create agricultural fields or pastures for cattle ranches. Deforestation required fire.

The end result of this massive migration of people and new road construction has been the unprecedented fragmentation of the region's forests, as communities of small land holders and large ranch owners work at 'improving' the land at scales of hectares to square kilometers.

Along with the new towns and paved roads came the industry of logging. Forests are heavily damaged during road building and tree felling activities for logging. These forests are often adjacent to large pastures. Furthermore, settlers in search of unclaimed lands frequently follow logging roads.

Now, there are vast stretches of pastures and agricultural lands along networks of established roads. Fire is the main tool used to establish and maintain these lands. Cleared lands are often reburned every two to three years (Fearnside 1990; Kauffman *et al*. 1998). Since fire-mediated deforestation continues to occur, this signifies that the number of intentional, human – caused ignition events in the Amazon will increase each year as growing amounts of land are treated with fire.

Unintended fires are increasing in likelihood and expanse as populations grow and the landscape becomes more interconnected by highly flammable vegetation. Fire ignition is intimately tied to the transportation network, as can be seen in the clustering of satellite detected fires along major roads. Logging activities are making several adjacent forests more susceptible to fire. Fires caused by loggers, hunters, and escaped land-maintenance burns are becoming more frequent and severe. The landscape is rapidly being converted from one of little or no fire to one of frequent and widespread fire.

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fire fighters with hand tools, fires in degraded forests can often be too severe for manual methods of control (Cochrane *et al*. 1999).

Starting a fire

For any fire to occur there needs to be an ignition event: a spark. The tropics receive more lightning bolts than anywhere else on Earth but the rain that usually comes with them is the forest's protection. Even if a fire is started it will go out; the green and moist vegetation surrounding it keeps the humidity so high that even dead leaves will not burn. Consequently, without fire to act as a selection pressure for species survival, the vegetation in tropical evergreen forests has not needed to develop resistance or adapt to frequent fire disturbance.

For thousands of years, man has used fire to clear land for agriculture and to help in countless human tasks (Pyne 1997). The result has been a ready source of ignition not dependent on weather events. It became a matter of time before fire escaped into the forest. Under extreme drought conditions of periodic mega-*El Niño* events, frequent escaped fires may have been widespread and severe enough to have influenced the distribution and migration of indigenous people (Meggers 1994). Today, widespread ranching and logging, in addition to swidden agriculture, is causing the problem of fire in tropical forests to grow quickly. Unless significant changes are made in land use management techniques, the number of ignition sources will continue to

Typical Fire Management

Efforts to prevent the fire from escaping, if any, frequently depend on the individual farmer's preference or judgment, since regulations or enforcement are often lacking. In many cases the fire is simply set so as to burn into the forest margin, where it will normally go out after entering only a few to several meters. When new plots are adjacent to existing plots or pastures, a 1-2 meter wide firebreak is frequently made by removing all vegetation between the plot to be burned and the areas to be protected. In larger – scale operations tractors may be used to clear even wider firebreaks. Fire is the only means a farmer has of making the land tenable for agriculture and, so, the farmer uses this tool to his advantage while trying to avoid collateral damages to other valued property.

grow, as well as the probability of forest fires. This combination means that, although the severity of each year's fire season will, as always, vary with the annual climate, fire risk will tend to increase every year.

Land use issues

Land use is a critical issue in fire management in the tropics. The three main land uses in the tropics are agriculture, ranching and selective logging. Each of these three land uses feeds into the fire situation in the tropics and will require adaptation to reduce both the risk and the extent of the fire problem.

Slash-and-burn agriculture has been practised for thousands of years in the tropics (Pyne 1997). Within a desired plot, most or all of the trees are felled and then left to dry for up to several months. Seasons are variable across the tropics of Latin American and the Caribbean tropics, but in most regions there are one or more dry seasons that determine when the practice of slash-and-burn can take place.

The dry season is also the fire season. Once the slashed materials are dry enough to burn, the farmer will set fire to the felled vegetation in the late morning or early afternoon. The objective is to reduce the pile of debris by as much as possible, while releasing the contained nutrients so that they may act as fertilizer for the soon-to–be-planted crops.

Newly-opened lands will be planted with whatever crops are regionally appropriate and the plot will be farmed for as long as it is productive. When productivity wanes, the plot may be turned to pasture for cattle or fallowed for a time. If fallowed, the forest will be allowed to regrow and replenish many of the nutrients at the site. If fallow cycles between cuttings are long enough, this is a sustainable practice, but, as population pressures increase, fallow cycles are often shortened and productivity drops.

Ranching within the tropics is widespread, but variable in size and intensity. As practised in the tropics, cattle raising can consist of one or more cows grazing on a few hectares of recently fallowed land or of several thousand head of cattle being moved around to graze various pastures on extensive land holdings. The process for clearing land for pasture is largely the same as for slash-and-burn agriculture, but the clearing often occurs on a larger scale

as extensive tracts of land are converted to pasture. A newly-created pasture may be seeded with grass or simply allowed to regrow. In either case, the pasture will become increasingly overgrown, as second-growth vegetation from the forest starts to take over. These pastures can either be cleared by hand with machetes or, as is more commonly practised, burned again to kill off the forest regrowth (Mattos and Uhl 1995). In general, pastures will be reburned every two to three years (Kauffman *et al*. 1998; Fearnside 1990).

In 1996, between 1 000 000 and 1 500 000ha of forest in the Brazilian Amazon were selectively logged (Nepstad *et al*. 1999). This is going on throughout many of the tropical forests in Latin America, although forest locations, extraction amounts and intensities are often poorly reported. All countries with tropical forests produce wood products and fuel for domestic markets, but Brazil and Bolivia and, to a lesser extent, Nicaragua, Belize, Guyana and Suriname also export tropical woods (FAO 1999).

Methods and intensities of selective timber extraction vary from place to place. In the Brazilian Amazon five main models of logging have been identified, two in flooded varzea forests and three more in *terra firme* forests (Uhl *et al*. 1997). Both the number of species and the number of trees extracted from an area increase as the frontier ages and logging markets expand. Selective logging may occur on a small scale as a precursor to deforestation, or it can be a highly mechanised and industrial operation over a large area. Those logged forests, close to pastureland and agricultural areas, are more likely to have fires.

The Effects of Selective Logging

The impacts of selective logging vary with extraction intensity, but can be substantial. Selectively logged forests would be expected to accumulate carbon over time and recover to pre-harvest levels of biomass if left undisturbed. However, many forests are revisited several times when loggers return to harvest additional tree species as regional timber markets develop (Uhl *et al*. 1997; Veríssimo and Amaral 1998). These forests become very degraded and may have 40 – 50 per cent of the canopy cover destroyed during these logging operations (Uhl and Vieira 1989, Veríssimo *et al*. 1992). The effects of selective logging include increased fire susceptibility (Holdsworth and Uhl, 1997), damage to nearby trees and soils (Johns *et al* 1996), increased risk of local species extirpation (Martini *et al* 1994), and emissions of carbon (Houghton 1995). Furthermore, uncontrolled exploration by loggers catalyses deforestation by opening roads into unoccupied government lands and protected areas that are subsequently colonised by ranchers and farmers (Veríssimo *et al* 1995).

Landscape Fragmentation and Land Cover Change

Landscape fragmentation and land cover change are important elements in changing the level of fire risk within a region's forests (Goldammer 1999). The extent of the effects of forest fragmentation are illustrated in the Amazon forest. Skole and Tucker (1993) estimated that, by 1988, fragmentation and its associated edge effects (e.g. wind exposure, excessive drying, invasive species, etc.) had affected an area of forest 50 per cent larger than the one that had been deforested. Within the forest, fragmentation can result in biomass collapse and increased mortality out to at least 100-300m (Laurance *et al*. 1997; Laurance *et al*. 2000), which can make these forests more susceptible to fire. Every metre of exposed forest can allow fire to enter and increases the risk because more edge is exposed to more fire, more frequently.

Two locations in the eastern Amazon illustrate the importance of fragmentation and edge formation for a region's forests: Paragominas is an older frontier first settled in the mid-to-late 1960s, dominated by large ranching and logging interests; Tailândia is a newer frontier area created as a settlement project by the Brazilian government (INCRA) for small landholdings.

The pattern of fragmentation differs in both locations but the end result is the same. In both regions more than 50 per cent of the remaining forests exist within 300m of a forest edge. Fire regularly penetrates the forests of both sites for more than a kilometre and so nearly all remaining forests in these areas are being affected (Cochrane 2001).

Land cover change is also making the fire problem in the tropics worse. The main problem is the increasing prevalence of adjacent flammable ecosystems (e.g. pastures). In the past, agricultural plots and pastures existed as islands of easily-flammable vegetation within a sea of largely fire immune forest. However, as a region develops, its forest remnants become increasingly fragmented and surrounded by large pastures of easily-flammable grasses. This can lead to fire escaping into neighbouring pastures, directly increasing economic costs and the total area of forest exposed to fire.

Selective logging also causes problems by opening the canopy and allowing the forest to dry out. Logged forests, with their heavy fuel loads and porous canopies, become easily-flammable vegetation which further links the region's pastures and exposes more forest to potential fires. Burning becomes highly likely due to their proximity to fire-maintained pastures and the propensity for unplanned settlement to occur within them. People searching for accessible land follow logging roads into these damaged and fire-prone forests to begin slash-and-burn agriculture (Veríssimo *et al*. 1992).

Forest fires can severely damage forest canopies and make them function like the logged forests described above.

Landscape fragmentation and land cover change interact to expose more of the forest to fire and consequently raise the risk of fires occurring across the landscape which becomes increasingly porous, allowing fire contagion to spread more easily. Fire risk management efforts will therefore have to

take into account both landscape configuration and land cover types in emphasising fire prevention or responses to fire events.

The Fire Dynamic

Under the proper climatic conditions, even large tracts of undisturbed forests can burn. Such was the case in Roraima, Brazil, in 1997 and 1998, when fires burned an area of 3 814 400 - 4 067 800ha of which 1 139 400 - 1 392 800ha was intact primary forest (Barbosa and Fearnside 1999). Though the *El Niño*-spawned drought made these forests highly flammable, the fires themselves were caused by the rapidly-growing population of rural residents.

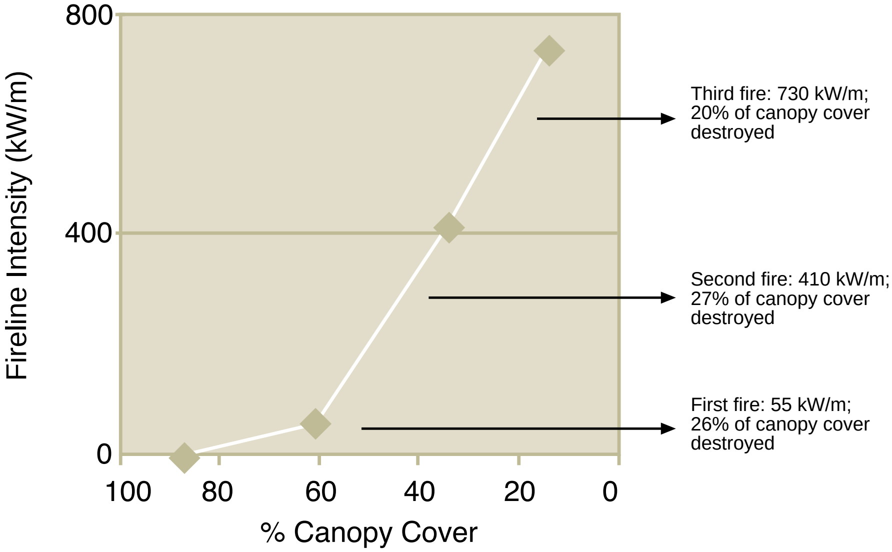
Burning has also been observed in large areas of previously-logged forests, including a 100 000ha burn near Paragominas (1988) and a 9 000ha burn around the community of Del Rei (1991-92) (Stone and Lefebvre 1998). Beyond issues of scale, it is disturbing that these fires can start a cycle of increasing fire susceptibility (Cochrane and Schulze 1999), increasing fuel loads and increasing fire severity (Cochrane *et al*. 1999). Logged forests (Uhl and Kauffman 1990), especially those within several metres of deforested edges (Cochrane 2001), are especially at risk from fire. Both recurrent logging and fire can dramatically change forest structure and lead to extensive invasion of flammable vines and grasses (Uhl and Kauffman 1990, Veríssimo *et al*. 1992, Cochrane and Schulze 1999).

The first fire in an intact closed canopy forest is unimpressive. Except for tree-fall gaps and other areas of unusual fuel structure, the fire will spread as a thin, slowly creeping ribbon of flames a few tens of centimetres high (Cochrane and Schulze 1998). Over much of the burned area, the fire will consume little besides leaf litter. In its immediate wake, however, the fire will leave a strangely open understorey of dying seedlings and saplings with shrivelled leaves, although the canopy trees appear relatively unscathed. By 17-18.00 hours, as temperatures drop and relative humidity levels increase, the fires often die out. By nightfall, only a few smouldering logs remain, to be re-ignited in the mid-to-late morning if conditions allow. Behind the fire line, leaves will begin to fall from newly-killed trees, replenishing the pool of fine fuels. The fireline may move only 100-150m a day, but can keep burning like this for days, weeks or months (Cochrane *et al*. 1999). If the weather is cool or a light rain falls, fires may not burn at all. Many areas will reburn one or more times as falling leaves continue to cover the ground. The density of large fuels (fallen boles, crowns and large branches) is an important factor in whether the fire will reignite.

Logged forest stands will be more likely to sustain fires over extended time periods, and to reburn within a single season. Furthermore, over the years after a fire, falling and dead trees will result in a greater load of large fuels which will keep fires going when weather conditions do not allow for active fire spread.

A fire as described does not seem anything to worry about, but in fact, it is a big problem. The fireline intensity is very low, similar to prescribed fires (50 kW/m) in temperate forests. The slow advance of tropical fires, however, makes them deadly

Figure 1. Comparison of fire intensity and effcts on forest canopy for recurrent fires in a tropical forest



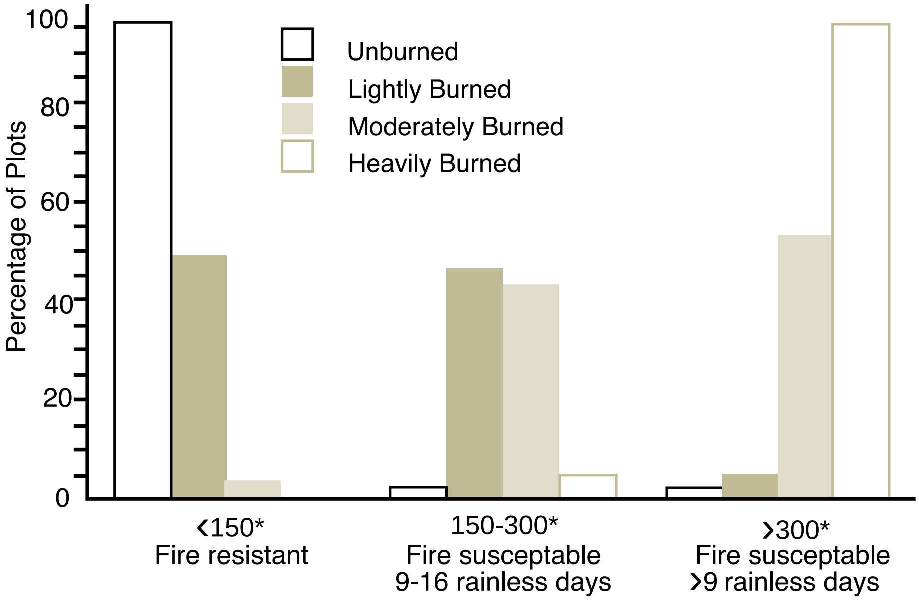
Source: Cochrane 2000 a.

due to the length of time flames stay alight at the base of fire-contacted trees. Imagine a candle flame. You can pass your hand through the flame quickly without causing any harm. Now imagine holding your hand over the flame for one or two minutes. It is a small fire but it will cause a severe burn. It's not the size of the flames that do it, it is the length of contact that determines the damage they cause. In the Amazon, most of the trees have very thin bark and are therefore highly susceptible to damage by fire (Uhl and Kauffman 1990). Bark thickness increases with the diameter of the trees, which explains why smaller trees suffer most from these fires.

The fire kills many trees and the forest loses much of its canopy cover (Figure 1). More sunlight reaches the forest floor and this increase in sunlight raises the temperature. An intact forest will rarely exceed 28˚C on even the hottest days, but after fire thins the canopy, the forest may reach 38˚C on a similar day (Uhl and Kauffman 1990). This makes the forest much more vulnerable to a new fire (Figure 2).

Prior to burning, canopy cover averages 85 per cent to 95 per cent and the humidity beneath the canopy remains high even during the dry season; only small disjointed areas (typically less than five per cent) such as tree fall gaps become fire susceptible after 16 rainless days. A year after the fire, canopy cover is roughly 60 per cent and the capacity to maintain high humidity is much reduced, with half of the forest becoming susceptible to fire under the same weather conditions (Cochrane and Schulze 1999). In addition, as the trees that were killed by the fire begin to fall or shed branches, the amount of both small and large combustible materials on the forest floor increases (Cochrane *et al.* 1999). Such a fire would kill nearly 40 per cent of the trees (>10 cm diameter), but reduce living biomass by as little as 10 per cent,

Figure 2. Effect of recurrent tropical fires on future fire susceptibility.



Note: Forests that are more severely burned or those burned many times (light = 1x, moderate = 2x, heavy = >2x) become much more prone to future fires. Grap[h shows the percentage of a given rainforest type which is likely to become fire-susceptible after either 9 or 16 days without rain.
* The numbers refer to the rate of direct photon flux density (PFD in minutes of mol/m^2/d)

Source: Cochrane and Schulze 1999

since few large trees, which comprise the majority of the biomass, would be killed (Cochrane and Schulze 1999).

These forests are much more likely to burn in the future. If a forest reburns within a few years of the initial fire, the fire will be much worse. Flame lengths, flame depths, spread rates, residence times and fireline intensities are all significantly higher. A second fire will kill another 40 per cent of the remaining trees, this time corresponding to 40 per cent of the living biomass. In forests that reburn, large trees have no survival advantage over smaller ones because the changes in fire behaviour overwhelm the defences of even the largest, thickest-barked trees. In other words, while the first fire killed mostly small trees, the second fire is just as likely to kill a large tree as a small one (Cochrane *et al*. 1999).

Weedy vines and grasses, some of which are quite flammable even when green, quickly colonise twice-burned forests. Canopy cover is further reduced to less than 35 per cent. The amounts of both live and dead combustible material increase rapidly and virtually all the forest will become fire susceptible within 16 rainless days. The process is clear: burning these forests creates a positive feedback in both fire susceptibility and fire severity. This means that the fires not only become more frequent, they also become much worse each time, and can end in the forest's obliteration.

Fires in selectively-logged forests will act like those in intact forests; the first fire may be very intense due to the large amount of slash fuels left over from the logging operation (Uhl and Kauffman 1990). In logged forests that burn there may be no survival advantage for larger

diameter, thicker-barked trees in an initial fire (Kauffman 1991) as has been reported in other tropical forests (Woods 1989; Cochrane and Schulze 1999). Therefore, the first fire in logged forests will degrade the site a great deal and make it much more vulnerable to recurrent fires.

The Fire Regime

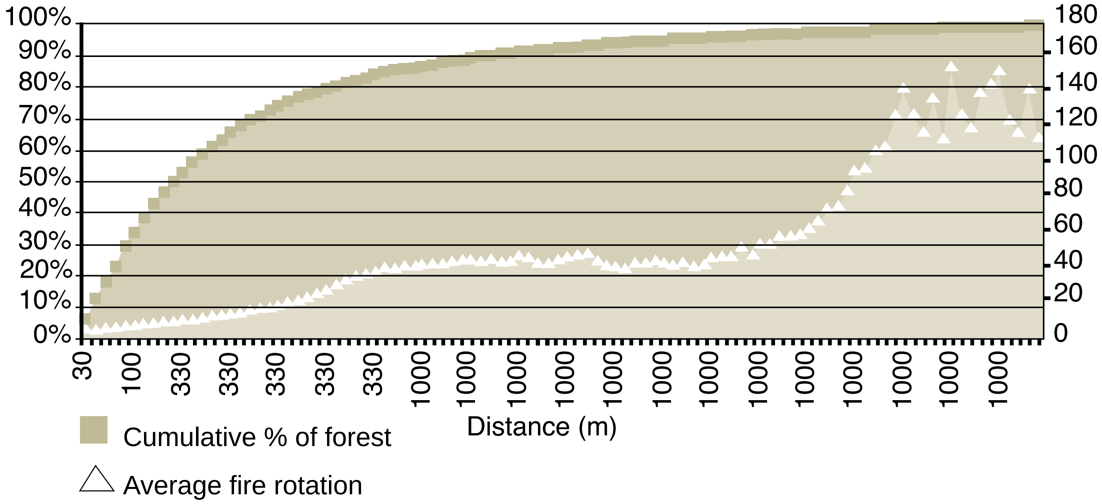
Shifts in the frequency, intensity and pattern of forest fires in the tropics represent a shift in the fire regime. The natural fire regime for tropical moist and tropical humid forests is one of little or no fire (Mutch *et al*. 1999). Fire return intervals of 1 000 years are quite usual (Hammond and ter Steege 1998). Vegetation responds to and also influences regional fire regimes. It is likely that over time the boundary between the tropical forests and cerrado or savanna vegetation has shifted back and forth under the influence of millennial climate variations. In drier conditions, the fires would push the forest back, while during wetter periods the forest would encroach into savanna and other fire-prone vegetation. In strongly seasonal areas, closed canopy forests are able to maintain high sub-canopy humidity levels even during the dry season (Moreira *et al*. 1997). However, when fire return intervals drop below 90 years or so, rain forests collapse and are replaced by more fire-tolerant vegetation (Jackson 1968).

Conditions throughout the tropics now differ substantially from the patterns of the past. Although high densities of indigenous peoples may have lived within these forests prior to European contact, most settlements were concentrated along rivers (Pyne 1997) and did not involve large-scale mechanised logging operations. Settlement patterns nowadays have opened up the upland terra firme forests to extensive settlement. Large-scale ranching and logging operations have further changed the way people are interacting with the landscape. The end result is a forest that has been changed by fire, and is likely to burn again.

Data from charcoal studies suggest a fire-return interval of at least 500-1 000 years (Cochrane 2000b). Existing fire rotations in tropical forests in some parts of the eastern Amazon suggest that over half the remaining forests will experience fire every five to ten years (Cochrane *et al*. 1999). The current fire frequency in many forests is sufficient to prevent any significant regeneration of current canopy trees (Figure 3). This suggests that tropical evergreen forests could be replaced by degraded, fire-resistant vegetation throughout much of the seasonally-dry Amazon (Cochrane *et al*. 1999; Cochrane 2001).

Data from the eastern Amazon show that, although most forest burning is occurring within several hundred metres of the forest edge, edge-related fires can penetrate at least 2.5km into forests. Additional, isolated burns, possibly caused by loggers or hunters, can occur at least as far as 5.5km from any forest edge (Cochrane 2001). In a sense, these additional burns can be considered a large-scale edge effect (Laurance 2000; Cochrane and Laurance, in press), as they are much more common within the first 10km than further into the forest. The result is an intensification of disturbance in the remaining forests in many regions to the point where tropical evergreen forests will not be able to persist.

Figure 3. Comparison of the cumulative percentage of existing forest and the freqyency of burning at different distances from defroested edges.



Note: Left hand axis is the cumulative percentage of forest and the right hand axis is the number of years between fires. Roughly 75 per cent of all remaining forests in this region (Tailàndia, Parà, Brazil) are expected toburn at least once every 20 years. Normal intervals between fires for these forests are greater than 500 years.

Source: Cochrane 2001

Land-use and climate change are interacting to create unprecedented stresses on Amazonian forests (Laurance and Williamson, in press), and the fire situation described here can be expected to worsen.

Without fundamental changes in land management practices, fire can be expected to impact vast reaches of tropical forest, degrading and eroding forest fragments (Gascon *et al* 2000; Cochrane and Laurance in press) as well as accelerating predicted levels of species extinction (Pimm and Raven 2000). In terms of total area affected each year, forest fires are quickly overtaking slash-and-burn deforestation as the primary disturbance factor in tropical forests.

Regional and Global Climate Change

The fire situation in the tropics may be exacerbated by ongoing changes in both regional and global climate. Regional effects on climate are significant and potentially severe. Deforestation may contribute to regional drying by reducing overall levels of evapotranspiration during drier months. Water vapour from evapotranspiration is the main source of humidity in tropical evergreen forests during the dry season (Moreira *et al*. 1997). Extensive deforestation could reduce regional rainfall in the Amazon by as much as 20 per cent (Salati and Vose 1984) and lead to more frequent and longer droughts (Shukla *et al*. 1990). Recent research has also shown that smoke from tropical fires suppresses regional rainfall by creating an excess of cloud condensation nuclei that produce water droplets too small to precipitate (Rosenfeld 1999; Ackerman *et al*. 2000). Urban and industrial pollution has been shown to have similar effects on local rainfall patterns (Rosenfeld 2000).

Smoke released from tropical forest fires can have additional implications for fire on regional and continental scales. Specifically, in addition to reducing rainfall, smoke from fires in southern Mexico, in 1998, increased the amount of positive cloud-to-ground lightning as far away as New England, USA and Ontario, Canada (Lyons *et al*. 1998). Positive cloud-to-ground lightning strikes are usually uncommon, but can continue for months in the wake of large smoke plumes. Furthermore, overall peak currents of such lightning strikes double in smoke-contaminated clouds (Lyons *et al*. 1998). Positive cloud-to-ground lightning strikes are more likely to cause fires than other lightning types and their increased frequency and intensity can increase the number of natural fires over wide regions.

Global warming may also change the current fire situation in the tropics. Models based on a doubling of current CO_2 levels show a general trend towards warming and resultant increased amounts of rainfall. However, evapotranspiration from vegetation due to warmer temperatures is expected to exceed rainfall gains (Price and Rind 1994). Interannual climate variability and storm intensity are also expected to rise. Interactions between changing climate and human land use may result in changes in the disturbance regime of densely-populated tropical regions (Goldammer and Price 1998) that can eliminate tropical forests and replace them with scrub savanna (Cochrane and Schulze 1999; Cochrane *et al*. 1999; Cochrane 2000b).

In addition, under conditions of global warming induced by a doubling of ambient CO_2 levels, lightning strikes are expected to increase dramatically. Models show 44 per cent more in the United States, with a concurrent 78 per cent increase in total area burned due to lightning-induced fires. Overall, lightning strikes are expected to

The Effect of Frequent Fires in Tropical Forests

If fire incidence stays at current levels or increases in frequency, then this will cause many forests to be replaced with more fire tolerant vegetation over the coming decades. Post-fire regeneration of trees can be robust, consisting of vegetation resprouting from damaged trees (Kauffman 1991) and pioneer dominated seed germination (Uhl and Buschbacher 1985; Cochrane and Schulze 1998). Frequent fires prevent these trees from reaching reproductive ages though (Cochrane and Schulze 1999). Fire impacts will be worse where prolonged dry seasons occur. Large-scale selective logging can interact with fire to cause similar fire problems, even in wetter less seasonal forests (Uhl *et al*. 1988). The shift from a fire regime of little or no fire to one of frequent fire is consistent with that found in scrub and savanna (Hammond and ter Steege 1998). In the more seasonal tropics, the destruction of the current forest cover is likely to be irreversible under current climate conditions (Mueller-Dombois 1981; Shukla 1990).

increase even more substantially in tropical regions, in conjunction with a change in the overall water balance (i.e. precipitation – evapotranspiration and runoff) from positive to negative. The conjunction of drier conditions with more lightning ignitions could lead to growing numbers of fires in these fuel-laden forests (Price and Rind 1994). Such predictions tally with long term records from temperate Nothofagus rain forests in South America that link increased numbers of lightning-caused fires and total forest area affected by fire to drier years (Kitzberger *et al*. 1997). This situation could worsen if *El Niño* events become more frequent and intense in conjunction with global warming (Federov and Philander 2000). *El Niño*-spawned droughts, can make vast tracts of undisturbed tropical evergreen forest susceptible to fires in the Amazon (Nepstad *et al*. 1998; Nepstad *et al*. 1999). The accumulation of extensive areas of standing dead forests caused by previous fire incursions (Cochrane and Schulze 1999) also increases the possibility of lightning strikes igniting large fuels in rapid-drying, fuel-laden forests. Under such conditions, fire can persist by smouldering in large dry fuels, despite rain, and spread to the surrounding forest once the surrounding surface fuels dry out (Cochrane 2000a).

Trends in regional and global climate change may significantly alter the disturbance regimes in fragmented and human-disturbed forests (Laurance and Williamson, in press). Such changes will only exacerbate established positive feedbacks in the fire dynamic of the tropics (Cochrane *et al*. 1999) especially within a few kilometres of deforested edges (Cochrane 2001).

Rehabilitating Fire-impacted Forests

What can or should be done with tropical evergreen forests that have been impacted by fire? Should they be replanted, abandoned, protected or converted to other land uses? There is no simple answer. Post-fire actions within any burned forest stand will depend upon the total area affected, the degree of damage sustained, its protection status or perceived importance, and the resources or funds available.

The amount of forest that is impacted by fire will vary from year to year. The size and intensity of wildfires will be a result of climate and fire response activities. If burning forests have been previously undisturbed, fire damages will likely be light and affect mostly smaller sub-canopy trees (Woods 1989; Cochrane and Schulze 1999; Peres 1999, Barbosa and Fearnside 2000; Nascimento *et al*. 2000). Areas which have been previously logged or burned may burn intensely, killing even large trees, and severely damaging the forest canopy (Kauffman 1991; Holdsworth and Uhl 1997; Cochrane and Schulze 1999).

One thing that all burned forests have in common is an increased susceptibility to additional fire incursions. Therefore, if the process of fire degradation is to be arrested, it will be necessary actively to protect these forests from future fires. In the case of logged forests, it has been recommended that five-metre wide firebreaks be maintained around them for ten years after timber extraction (Uhl *et al*. 1997). Similar protection will be necessary for burned forests. In the case of logged forests that burn, and any forests that burn several times, it may take several

decades of fire protection to allow them to recover appreciably (Cochrane and Schulze 1999). The construction and maintenance of firebreaks should, with post-disturbance fire protection, be an integral element of fire prevention. Simple legislation requiring construction of firebreaks is, however, unlikely to be effective as they cost landowners a large percentage of their annual income for no obvious or immediate gain. These costs disproportionately affect smaller, poorer landowners (Nepstad *et al*. 1999b). Where possible, financial incentives should be used to encourage better fire management behaviour. Landowners could perhaps be compensated financially for the external benefits provided by their forests. Costa Rica has already linked the maintenance of environmental services derived from forest cover such as carbon sequestration and hydrological services to their domestic market (Chomitz *et al*. 1999) and similar programmes could be applied throughout Latin America.

In the case of many fire-impacted forests, natural regeneration from resprouting vegetation (Kauffman 1991) and surviving seed banks in the soil (Uhl *et al*. 1981) should be sufficient to rapidly restore the forest understorey. Reproductively-mature canopy trees will also continue to provide a seed source to the forest. Fire-impacted forests will have substantially higher densities of pioneer vegetation for decades to come (Cochrane and Schulze 1998) but can regain complete structural integrity in five to ten years.

In severely degraded forests, it may be necessary to reforest actively in order to speed the recovery process. A major limitation for the restoration of tropical evergreen forests, however, is the lack of knowledge about how to rebuild these complex ecosystems. Tropical evergreen forests typically have dozens or even hundreds of species of trees per hectare. No seed sources or propagation techniques exist for most species. In some forests, such as the Chimalapas in Mexico, human reforestation efforts have been considered to potentially do more harm than good (Ferriss 1999). In many cases, however, enrichment plantings with valuable timber species may provide an added incentive for landowners to provide continued protection from fires. Reforestation efforts should also be encouraged along steep slopes and other areas at risk of substantial soil erosion.

If nothing is done to protect or restore fire-damaged forests the result will be rapid forest degradation and a deteriorating ability to control fire across the landscape. As more degraded forests accumulate, forests fires will become more common and more widespread. Increased fire contagion will impact residents of the affected region by damaging crops and properties. The increased risk of fire will tend to make investment in perennial crops or tree plantations unattractive and promote more fire-tolerant activities such as ranching. In addition to direct effects on the population, the fires will indirectly harm residents via smoke-caused or antagonised illnesses. In regions where the fire situation can not be arrested, large amounts of fire-induced deforestation will occur and more fire tolerant scrub or savanna vegetation (Cochrane *et al*. 1999) will replace tropical evergreen forests.

Tropical wildfire impacts

Wildfires have raged over the last few years all over the world and no single country has been able to withstand wildfires without help. Countries affected include Indonesia, Papua New Guinea, Australia, Mongolia, the Russian Federation, Colombia, Peru, Kenya, Rwanda, Brazil, Mexico, Nicaragua, Honduras, the United States and Canada.

Even the United States, the world's richest nation, was not able to deal with the 2000 fire season alone. Despite mobilising all its fire-fighting resources, additional military units and even retired fire-fighting personnel, it had to call on fire-fighting assistance from several other countries: Mexico, Canada, Australia and New Zealand. The National Interagency Fire Center (NIFC) has long-standing agreements with several countries to provide mutual support in times of crisis and had provided 800 fire fighters to Canada in 1999 and technical, financial and equipment support to Mexico during 1998 (NIFC 2000).

Small wonder, then, that less-developed countries cannot effectively respond to widespread forest fires. In Indonesia, attempts at reducing the region's fire load were largely ineffective, despite efforts by the government, with support from Malaysian volunteers and fire suppression aircraft from Australia and the United States.

Reasons cited for this failure include (Barber and Schweithelm 2000):

- poor coordination between air and ground forces;
- lack of equipment;
- lack of funds;
- lack of water;
- insufficient training;
- the remote location of many fires;
- lack of accurate land cover maps;
- lack of infrastructure, and
- the reluctance of local people to fight fires on other people's lands.

Problems in Latin America were very similar to those faced in South East Asia.

There is obviously a need for interagency and international cooperation in fire fighting efforts. Crisis situations are neither the time nor the place to start working together; collaboration needs to flow from long-standing, coordinated regionally-integrated fire response forces. Similar coordination and cooperation should be fostered throughout Latin America.

The Fire Situation in Latin America and the Caribbean

South America

In South America, the fire situation has been just as serious. Brazil continues to have substantial numbers of fires in its tropical forests every year (Cochrane and Schulze 1998). In 1998 (see case study) the massive fires in the northern Amazonian State of Roraima alone burned in excess of a million hectares of standing forests (Barbosa and Fearnside 1999). Fires predominate in the states of Matto Grosso and Pará but are becoming more common throughout the Amazon. Large tracts (100 000ha) of normally-flooded forests (*igapo*) are also reported to have burned during 1997 in the central Amazon (Nelson, in press). Remaining fragments of

Brazil's Atlantic rain forest (*Mata Atlantica*) are similarly affected by fire and at particular risk of destruction.

In Bolivia, between 6-12 October 1999, 351 fires devastated more than 3 000 000 hectares and destroyed more than 600 homes, affecting at least 7 000 people (UNEP 2000). The smoke caused an increase in the number of cases of conjunctivitis and respiratory problems. The fires destroyed 100 000 hectares of wheat and soybean fields and damaged large tracts of forest. Staple foods were sent to alleviate hunger (Musse 1999) in the hardest-hit regions. Forest fires have invaded both tropical dry and moist forests. In tropical moist forests they kill more trees than in tropical dry forests (Mostacedo *et al*. 1999) as the thicker bark of trees in dry forests (Pinard and Huffman 1997) have greater fire resistance (Uhl and Kauffman 1990). Logged forests in particular are burning at an alarming rate, resulting in recurrent fires and post-fire vine profusion (Pinard *et al*. 1999).

Other recent fires in South America include the extensive complex of 1998 fires that burned through forests in parts of Brazil, Colombia, Venezuela, Guyana and Suriname. In Venezuela, Colombia, and Guyana tropical moist forests were particularly affected, while in Suriname coastal swamp forests and mangroves were also burned. In Suriname, the hardest-hit regions were Wageningen and along the Courantyne river. In Guyana the worst-affected communities were Marlborough, Georgetown and New Amsterdam (Grégoire, J.M. *et al*. 1998). In Guyana, additional fires impacted rural regions of southern and western parts of the country, including a 2 000-hectare forest fire in the Mabura-Rockstone area. The government was particularly concerned about fires burning in districts too far from fire brigades (Wilkinson 1998). Fires raged along the savanna-forest contact regions of Brazil and Venezuela. Despite the documented fire resistance of these forests (Biddulph and Kellman 1998), over a million hectares burned, and the fires penetrated many kilometres into the interior (Barbosa and Fearnside 1999). Forests in these regions have survived a varying climate over the millennia but trees can not re-establish without protection from fire (Aide and Cavelier 1994; Cavelier *et al*. 1998) and once destroyed, these forests are unlikely to return, even if the climate is moister (Rull 1992).

Additional fires in the Latin American tropics have occurred in areas as diverse as the Inca ruins of Machu Picchu (Koop 1997) and Manu National Park in Peru (Associated Press 1999) and the Galapagos islands of Ecuador (Wikelski 1995). Fires have recently occurred in the temperate forests of Chile (Haltenhoff 1999) and Argentina (Tesolin 1993; Sipowicz 1994). Though temperate, the Nothofagus rain forests of Chile and Argentina burn, like tropical evergreen forests, only during extended droughts (Kitzberger *et al*. 1997) and may therefore be under similar pressures from fire.

Central America and Mexico

Nicaragua has a serious fire problem due to a lack of human, material and financial resources and is currently restructuring its fire management programme (Mutch *et al*. 1999). Between

December 1997 and April 1998 Nicaragua had over 13 000 fires, more than any other Central American country, and over 11 000 fires in April 1998 alone (FAO 1999). The fire situation in 1998 was worsened due to the *El Niño* drought. There were twice as many fires in 1998 than in 1996 and 1997, caused by drought, and concentrated in the tropical evergreen forests of the wide Atlantic plain (Jacques de Dixmude *et al*. 1999).

Throughout Central America, over 2.5million hectares were affected by fire in 1998, most severely Nicaragua, Guatemala and Honduras (900 000, 650 000, and 575 000 hectares respectively). Panama had over 200 000 hectares of land affected by fire while nearly 100 000 hectares burned in Costa Rica and less than 50 000 hectares burned in Belize and El Salvador.

Costa Rica and Honduras have well-organised fire fighting forces. Guatemala was moderately prepared for the fires of 1998 (Mutch *et al*. 1999) but the Petén region continues to suffer from illegal logging and escaped fires (Gonzalez 2000).

Belize's Forestry Department's maps of burned savanna areas from 1959-1982 show the effect of fire suppression. In fire-controlled regions, fires return intervals increased to about 100 years, whereas in unmanaged areas, fires return intervals were 18 years. Although prescribed fires have since dropped fire return intervals to roughly 50 years, tropical gallery forests on savanna margins have been burning at an average interval of only 38 years (Kellman and Meave 1997).

Mexico had severe fire problems in 1998, despite having a well-organised fire fighting

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force. The number of fires in 1998 was double the long term average and the area that burned was nearly five times the long term average. In all, nearly 850 000 hectares burned in 1998 (see case study). Severe fires in tropical evergreen forests in Chiapas, Oaxaca and Veracruz were of particular note, as the tropical forests that burned are particularly susceptible to recurrent fires. By 15 July 1999, both Oaxaca and Chiapas were among the ten states with the most fires. They were also numbers three and six, respectively, in terms of the total forest area affected by fire (SEMARNAP 2000). It is likely that these areas will require significant attention and resources over the next several years.

The Caribbean

There is little published information available regarding the fire situation. In Cuba, 88 per cent of fires are caused by human activity. Between 1984 and 1998 there were an average of 325 fires per year which burned an average of 4 878ha. Average fire sizes ranged from 10 to 30ha. The 1999 fire season seems to have been the worst on record. Inter Press (May 21 1999) reported that 258 fires had affected 10 000ha of forest by May 1999. A single fire in Cuba's largest forest reserve, Pinar del Rio, burned over 4 000ha (Acosta 1999). Cuba is not considered to have a serious fire problem (Rodriguez 2000).

In Trinidad and Tobago, a severe drought in 1987 resulted in over 20 000 hectares of forests burning, and stimulated the 1988 Forest Fire Protection Plan for Trinidad. Since then, the numbers of fires and total area burned each year have been substantially reduced. Though there were 50 per cent more fires during the *El Niño* drought of 1998 as compared to 1987, only 10 289 hectares burned (Mutch *et al*. 1999). In the Dominican Republic, the *El Niño* event of 1997 resulted in 225 fires that impacted 207 000 hectares of grassland and forest. The average number of fires in the previous five years had been 68, burning less than 50 000 hectares per year (UNEP 2000).

Wildfire Impact

Economic impact

The full economic costs of uncontrolled fires in the tropics have not been well quantified and assessments are usually conservative. This is partly due to a lack of data or analysis, but also because cause-and-effect is complicated to assess, and full disclosure is politically tricky. Economic damages from uncontrolled fires cover everything from medical costs and airport closures to timber and erosion losses. Economic impacts are often indirect, and assessments may thus be conservative. In many cases, fires that directly affect one area may indirectly affect the health and economies of other regions or countries. These external costs of fire, through lost work days, production slowdowns and lost tourism dollars, are unlikely to show up in the accounting of the region or nation that is responsible. Furthermore, the linkage between a fire and its effects may be both obscure and delayed. A fire-denuded hillside may collapse in a mudslide and destroy a community years afterwards, or a year's crop production may be reduced by the killing of pollinators the previous year.

The economic impact of fires can be regionally severe and locally catastrophic, even if they are not significant on a national or global scale. For example, the 1998 fires in Roraima, Brazil are reported to have caused US$36 million in crop damages (CNN March 14 1998). This may not sound so bad until it is realised that this included 80 per cent of the state's staple bean, rice and corn crops (Kyodo News Service March 14 1998). In Mexico, the slow-down in industrial production to reduce pollution within Mexico City, mandated due to smoke from forest fires, is estimated to have caused economic losses of US$8 million a day (Goldammer 1999). Throughout Latin America, the true costs of tropical forest fires are largely unknown. In the case of Roraima, relating the expected carbon release of 42.06 TgC (Barbosa and Fearnside 2000) to its economic value as a greenhouse gas (US$ 20/ton; Fearnside 2000) yields a value of US$840 million.

The economic damages from the tropical fires in Indonesia have been better quantified. Actual fire-fighting costs for the 1997-1998 fires were not very high. Indonesia spent nearly US$12 million on fire fighting, and received another US$13 million in foreign aid. Neighbouring Malaysia, concerned about the impact of the fire, provided over 74 per cent of the aid (Ruitenbeek 1999). In comparison to the US$25 million used to fight fires in Indonesia during 1997-1998, the United States annually spends approximately $600 million (Elvidge *et al*. 1999) and is expected to exceed one billion US dollars in fire-suppression-related expenses in 2000 (Associated Press, August 31, 2000).

The economic costs of the fires go far beyond fire-suppression expenses, however. It is calculated that there were 2 446 352 lost workdays within Indonesia due to haze-related illnesses alone (Barber and Schweithelm 2000). The 1997 fires were estimated to have caused in excess of US$4 000 million in damage (Ruitenbeek 1999). A recent accounting of the full damages of the 1997-1998 fires estimates fire and haze-related damages of between US$8 800 and $9 700 million, roughly 5 per cent of Indonesia's gross national product (GNP). Agricultural losses made up 30 per cent of this but 67 per cent of the losses came directly from the loss of timber or environmental services. The cost of fire suppression (US$12 million) came to roughly 0.1 per cent of the total losses (Barber and Schweithelm 2000).

Although the exact value for losses in Latin America have not been calculated, it is quite probable that total losses equaled or exceeded those in Indonesia, where approximately eight million hectares were affected by fire in 1997-1998. A summary of the available data in Latin America for 1998 show that at least 9.2 million hectares burned. Since the record is incomplete, it is quite likely that total unintended burning in Latin America greatly exceeded 10 million hectares, excluding intentional pasture maintenance fires, which probably exceeded 20 million hectares in the Brazilian Amazon alone. The data do not exist for making a definitive estimate of the total damages within Latin America for the 1998 fires. However, if data from Indonesia are used as a rough measure, the damages in Latin America can be crudely estimated at $10 000 to $15 000 million.

Health Issues

The impact of wildfires on human health can be direct and indirect. Deaths are about as direct as it is possible to get: for example, 70 fire fighters were killed in suppression operations in Mexico in 1998 (Mutch *et al*. 1999), 14 firefighters have died in the United States during the 2000 fire season (Jehl 2000), 33 firefighters in Chile died in the field between 1970 and 1998 (UNEP 2000) and over 4 000 wildfire-related deaths have been reported from China between 1950 and 1990 (Goldammer 1999).

Most of the health impacts from wild fires come indirectly through the various substances and particles in the smoke released by the fires.

The health effects from smoke inhalation depend on the constituents of the smoke, its concentration, and the length of time the victim is exposed to it. Type and efficiency of burning determine the complex mixture of particles, liquids and gaseous compounds emitted by biomass combustion. The toxic mix of matter includes particulate matter of varying sizes, carbon dioxide, carbon monoxide, polynuclear aromatic hydrocarbons (PAHs), aldehydes, organic acids, semivolatile and volatile organic compounds, and ozone (Ward 1999). The effect of each of these different smoke components on human health is unknown, but the potential for adverse health effects is greatly increased. In south east Asia during 1997 and 1998, tens of millions of people were exposed to high levels of fire-produced gases and particulate matter (UNEP 1999). Millions more people were heavily exposed to smoke from tropical fires throughout Central America, Mexico, parts of the United States and the Amazon region of South America.

Inhalation of particulate matter less than ten microns in diameter has been linked to increased risk of mortality from both respiratory and cardiovascular problems, especially among children and the elderly. In Indonesia, there were only 527 reported deaths in eight haze-affected provinces during the 1997-1998 fires, but an accurate accounting of haze-related deaths is unlikely due to poorly kept records, and frequent misclassification or miscoding of the cause of death. Data on particulate densities that affected roughly 12 million people in this region suggest that the haze that was caused by the 1997-1998 fires may have been responsible for the deaths of nearly 31 000 people (Kunii 1999). The extent of haze-related mortality within the tropics is poorly-known and frequently underestimated. The smoke from the 1998 fires in the Brazilian Amazon is reported to have caused 700 deaths due to additional respiratory problems (Linden 2000). In addition to health-related issues, visibility problems caused by smoke released during tropical forest fires in Indonesia have been blamed for 27 deaths from two ships colliding and another 222 deaths in a Sumatran plane crash (Barber and Schweithelm 2000; UNEP 1999). Data are not available for counting the motor vehicle deaths and injuries caused by smoke-induced collisions each year throughout the tropics.

The health impacts caused by the fires go beyond mortality statistics. A survey of the general populace in smoke-affected regions

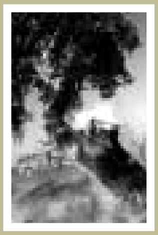
Table 5. The establishment of the pollution indices from Malaysia (API), Indonesia (HI) and Singapore (PSI) to monitor the levels of smoke-borne pollutants.

MALAYSIA Air Pollution Index (API)	INDONESIA Haze Index (HI)	SINGAPORE Pollutants Standard Index(PSI))	Diagnosis
0-50	1	0-50	Good
51-100	2	51-100	Moderate
101-200	3	101-154	Unhealthy
201-300	4	155-221	Very unhealthy
301-500	5	222-477	Hazardous
>500	6	>477	Extremely hazardous

Source: Derived from Shahwahid and Othman 1999; Hon 1999; and Ruitenbeek 1999.

of Indonesia showed that virtually 100 per cent had some negative symptom from the smoke and 90 per cent had respiratory difficulties. In some of the most severely-affected regions, the incidence of pneumonia was 33 times above normal levels. Even in less smoke-impacted regions, cases of asthma and pneumonia increased by 50 per cent. In addition, cases of bronchitis, acute laryngitis and bronchiectasis were up by 60 per cent, 800 per cent and 390 per cent respectively. One third of the general populace had conjunctivitis, while 67 per cent had constrictive lung disorder and 27 per cent obstructive lung disorder (Kunii 1999). Government statistics indicate that almost 1.5 million cases of acute respiratory infection were reported from among the 12 million residents of eight Indonesian provinces between September and November 1997 (Barber and Schweithelm 2000).

Standards are necessary for correlating levels of pollution to likely health problems to evaluate the potential effect of air pollution on human health so that appropriate action can be taken. Table 5 provides a comparison of various air pollution indices, with a human health diagnosis of the relative air quality. Air pollution is measured in different ways by different countries, a fact that makes comparison of pollution effects difficult. The Air Pollution Index (API) used by Malaysia estimates the current level of pollution based on the amount of fine particles (< 10 microns), carbon monoxide, sulphur dioxide, nitrogen dioxide and ozone present in the atmosphere (Shahwahid and Othman 1999). A similar index, the Pollution Standard Index (PSI) is used in Singapore (Hon 1999). Indonesia does not report a value for overall air pollution but does have a Haze Index (HI) (Ruitenbeek 1999) that can be correlated to other pollution indices. API values above 300 are considered hazardous. The API readings within the state of Sarawak, Malaysia were above 300 for much of September and October 1997 and reached levels as high as 849. Within East Kalimantan, Indonesia, API readings as high as 1 000 were recorded (Barber and Schweithelm 2 000) in October 1997. The long term implications



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of exposure to high levels of airborne pollutants have yet to be determined.

There do not seem to be similar air pollution indices in wide use throughout tropical Latin America. However, the hazardous levels of smoke-borne pollutants from tropical forest fires, could be measured as far away as Mexico City and even Texas in the United States (Latin American Institute 1998). The 40 per cent increase in smoke-related respiratory disease in Manaus (CNN October 9 1997) and the 10 000 Amazon-wide smoke-related hospital visits (Linden 2000), indicate that such indices need to be established.

Environmental Impacts

Environmental impacts from tropical forest fires range from local to global in scale. Locally, fire-damaged forests will be less able to retain water, exacerbating flooding and seasonal water shortages. The reduced, post-fire forest cover may also lead to increased erosion particularly on steep burned slopes. Research in Colombia has shown that up to 50cm of soil have been lost in areas where the forests have been removed by fire (Cavelier *et al*. 1998).

Other effects include regional climate change and impacts on local wildlife and biodiversity. A large percentage of the canopy is killed in burned tropical evergreen forests (Cochrane and Schulze 1999). Since water from evapotranspiration makes up most, if not all, of the normally high humidity in these forests (Moreira *et al*. 1997), if much of the foliage dies, the amount of transpired water is reduced, and the rate of drying in these forests increases

(Holdsworth and Uhl 1997). Within the Amazon Basin, as much as 50 per cent of the rainfall can be recycled from evapotranspired moisture (Salati and Vose 1984), so loss of vegetation due to burning may make regional weather dryer. Smoke-borne aerosols make this worse; by interfering with raindrop formation and reducing rainfall (Rosenfeld 1999; Ackerman *et al*. 2000). Forest structural changes and microclimate effects can combine to make forests more susceptible to recurrent fire (Cochrane and Schulze 1999) and result in replacement by scrub and savanna vegetation (Cochrane *et al*. 1999). The destruction of these forests releases large amounts of carbon into the atmosphere, in the form of various greenhouse gases, thereby contributing to global climate change.

The effects on wildlife can be locally severe. Slow–moving animals are at greatest risk of dying from flames and smoke. In Indonesia (Kinnaird and O'Brien 1998) and in Amazonian forests (Cochrane personal observation) reptile mortality in fire-impacted areas is believed to have been substantial Even if mammals, birds and many mobile animals are capable of escaping the flames they may not survive. Certain aspects of individual species' ecologies (diet, territoriality, and shelter requirements (Kinnaird and O'Brien 1998)) make many vulnerable to indirect fire affects. Escaping the fire is only the first step in survival. If the displaced animals can no longer find food, have territories of their own, or reach shelter, they will die of starvation or predation.

Trees are similarly affected. Initial fires selectively kill smaller, thinner-barked trees (Woods 1989), but subsequent severer fires can kill most if not all trees (Cochrane *et al*. 1999). Rarer species are most likely to be wiped out from a region (Cochrane and Schulze 1999). Flowering and fruiting of surviving trees in and near burned tropical forests decreases (Kinaird and O'Brien 1998) and damage from fire and logging can lead to the complete reproductive failure of forests several kilometres away as large numbers of frugivorous animals are forced to turn to remaining, unburned forest stands (Curran *et al*. 1999). The result is reduced biodiversity and a shift towards less robust pioneer species.

Perhaps the greatest impact on Latin America will be the millions of hectares of damaged tropical forests which are now unable to support the animals or plants that lived within them, and will thus become less valued by local people. They will become much more vulnerable to recurrent fires (Cochrane and Schulze 1999) which will be more severe because greater quantities of fuels will be available (Cochrane *et al*. 1999). These forests are likely to burn again and again, and fire managers need to watch them closely. Table 6 presents fire data from individual countries throughout Latin America and the Caribbean.

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Table 6. Average fire data and comparison data for fires during the 1997-1998 *El Niño* event for selected countries in Latin America and the Caribbean.

	Average				1997 - 1998 *El Niño* event				
Country	# of fires	Area burned (ha)	Average burn size (ha)	Time period	# of fires	Area burned (ha)	Average burn size (ha)	Region or land cover	Source
CARIBBEAN									
Cuba	325	4 878	15	1984-1998	259	4 144	16	All Land	Rodriguez 2000
Dominican Republic	68	49 400	724	1992-1997	225	207 000	920	All land	UNEP 2000
Trinidad and Tobago	314	4 264	13.6	1987	764	10 289	13.5	All land	Mutch et al.1999
CENTRAL AMERICA									
Belize						<50 000		All land	Mutch et al.1999
Costa Rica						100 000		All land	Mutch et al. 1999
El Salvador						<50 000		All land	Mutch et al. 1999
Guatemala						650 000		All land	Mutch et al. 1999
Honduras	2 701	64 282	23.8	1978-1989		575 000		All land	Salazar 1990; Mutch et al. 1999
Mexico	7 198	181 109	25	1992-1997	14391	848 911	59	All land	SEMARNAP 2000
Nicaragua	5 970	373 299	62.5	1988-1997	>13 000	911 760		All land	Mutch et al. 1999
Panama						>200 000		All land	Mutch et al. 1999
						41 298		All land	UNEP 2000
SOUTH AMERICA									
Argentina		1 308 713		1985-1989				All land	Tesolin 1993
		55 370		1985-1989				Forested	Tesolin 1993
		1 101 760		1981-1990				All land	Musse 1999
Bolivia		15 000		1987				Unknown	Musse 1999
		>3 000 000						Partial	
	>351	0	>8 547	1999				Bolivia	UNEP 2000
Brazil		27 960		1981-1990				Unknown	Musse 1999
	>45 000			1997		>5 500 000		Partial Amazon	Laurance and Fearnside 1999; Barbosa and Fearnside 2000; Cochrane et al. in press
Chile	5 359	48 227	9	1988-1997	5 329	90 888	17.1	All land	Haltenhoff 1999
	3 414	42 822	12.5	1963-1998	5 329	90 888	17.1	All land	Haltenhoff 1999
	5 260	53 192	10	1989-1998				All land	Mutch et al. 1999
		55 333		1981-1993				All land	Musse 1999
Colombia					>7 000			Unknown	Brown 1998
Ecuador		12 750		1985; 1994				Unknown	Musse 1999
Paraguay		60 000		1988				Unknown	Musse 1999
Uruguay		8 240		1981-1990				Unknown	Musse 1999
Venezuela	1 546	45 100	29	1982-1991				All land	Mutch et al. 1999
		511		1981-1991				Unknown	Musse 1999

The countries in Latin America and the Caribbean for which no data are available are not included in Table 6.

Mexico

During the *El Niño* event of 1998, a dome of high pressure dominated weather patterns over Mexico and Central America from March to May. Regional rainfall fell to less than 25 per cent of normal. High temperatures worsened the effects of the extreme drought. By mid-May, the US Embassy in Mexico declared the resulting fires a disaster. Similar declarations soon followed from Guatemala, Honduras, El Salvador, Nicaragua and Costa Rica (Le Comte 1999).

By mid-May, drought conditions and indiscriminate fire use had already combined to burn over 200,000 hectares of grasslands and forests. Fires raged in most Mexican States, but were most severe in the normally humid south-eastern states. During April, in Chiapas, tropical forests received a mere 0.2cm of precipitation instead of the usual 3.3cm. As temperatures soared to 35°C, humidity levels in tropical forests were reported to have fallen to as low as 10 per cent. The typically humid forest fuels became tinder dry. Normally-containable slash-and-burn fires and other land maintenance fires soon crackled into wildfires as the forests, which traditionally acted as green firebreaks, became dry, fuel-laden avenues.

In some states, marijuana and opium producers were blamed for many of the escaped fires. Reports from the state of Michoacán cited deliberate fires being set by drug traffickers as diversionary tactics to divert the attention of the authorities (Latin American Institute 1998).

As the fires continued, the situation became politically charged. Mexico’s Environmental Secretary was strongly criticised in Congress for having minimised the gravity of the fire situation by saying that, although SEMARNAP was concerned about the severity of the fire season, the conditions were "within historic parameters". Opposition parties took the opportunity to attack the President’s administration for having cut the 1998 budget for environmental programmes by 250 million pesos (US$ 29.3 million) (Latin American Institute 1998).

In the meantime, temperatures continued to rise to new records and extensive wildfires burned in the States of Oaxaca, Chiapas, Veracruz, Coahuila and Durango. One of the largest fires burned over 1 500 hectares of tropical moist forest in Oaxaca. Smoke from the many fires caused several airports in Mexico to be closed. Heavy clouds of smoke dimmed the sun as far north as Illinois in the United States and many residents of Texas were warned by health officials to stay indoors and refrain from exercise until the smoke cleared (Newman 1998). Within Mexico City, already severe pollution problems were exacerbated by smoke from the raging wildfires.

On May 25 1998, ozone levels in Mexico City were measured at 251 on a scale where 100 is considered unsatisfactory and 200 is potentially life-threatening to children and people with respiratory problems. As a result, factories had to curb production, schools cancelled outdoor activities, and nearly 40 per cent of the city’s vehicles were prohibited from being driven. Unusual winds continued to carry smoke from hundreds of out-of-control forest fires into the far north of the Rocky

Mountains and the Great Plains in the United States (Associated Press May 25 1998).

By early June, The United States Agency for International Development (USAID) had pledged $5 million to help with Mexican fire-fighting efforts. Technical experts from the United States also began helping to combat several fires burning out of control in Oaxaca's, Chimalapas biological reserve, one of the most important tropical rain forests in the Americas. The United States was particularly interested in these fires, because the rain forest contains about 1,500 of the world's most endangered plant species. It is a stopping point for 90 per cent of the United States migratory birds, and its plants contribute ingredients to about 130 of the most-used pharmaceuticals in the United States (Price 1998).

Fire-fighting efforts in Chimalapas proved difficult (Associated Press 1998) and illustrate the problems inherent in fighting forest fires in tropical rain forests. As a result of the lack of readily-available fire-fighting equipment, local people with kerchiefs over their faces fought the fires with tree branches (Ferriss 1999). In many cases, dense smoke prevented both firefighters and aircraft from reaching fires within the reserve. Even when helicopters could approach the fires, the peculiarities of closed-canopy tropical forest fires made effective fire suppression difficult. The fires were on the forest floor, separated from the helicopters above the still green and closed canopies which obscured direct sight of the fires and dispersed the smoke. The dense canopies dispersed the water before it could reach the ground (Price 1998and the vegetation made the burning forests all but impenetrable to firefighters (Hanna 1998). Some local citizens hiked six hours or more into the forest to cut landing zones for helicopters to drop firefighters (Ferriss 1999).

By June 5, more than 60 Mexican firefighters had lost their lives and, despite light rains, 144 wildfires continued to burn, including 23 large fires (Price 1998). By June 10, a pall of smoke spread from Mexico to as far north as the Dakotas and as far east as Florida (Gunson 1998).

The weather finally changed across much of Mexico as a tropical weather front moving along the east coast combined with Hurricane Blas on the west coast to provide much-needed rains. These, and the efforts of more than 1,300 firefighters, reduced the number of wildfires in Mexico to 34 by June 26. As early as June 18, only 17 fires were considered to be out of control, with 11 listed as large priority fires: five in Chiapas, three in Tamaulipas and one each in Nuevo Leon, Hidalgo, and San Luis Potosi. The dampening of the fires also put an end to the extensive smoke intrusions into the United States (Hanna 1998) who provided Mexico with over $8 million in disaster relief and supplied 50 advisors for technical expertise and assistance (Edwards 1998).

By the end of the fire season of 1998, more than 70 people, including many local volunteers, had died trying to control fires (Castilleja and Stedman-Edwards 1999). SEMARNAP records show that 14,391 fires, of an average size of 59 hectares, had burned a total of 848 911 hectares. This was more than double the long term average number of fires and more than a

four-fold increase in the total area burned (SEMARNAP 2000). Six thousand firefighters altogether were involved, plus an additional 139 000 elements of the Army and thousands of volunteers. Instead of the three planes and six helicopters SEMARNAP deployed in 1995-1997, a total of 57 planes, 25 helicopters, three Skycranes and a CL-415 from Mexico, the United States and Canada participated in fire-fighting efforts. In 1998 these efforts cost the Mexican Federal Government a total of 290 million pesos (US$33.3 million), several times the 40 million pesos budgeted for fire suppression. These figures do not reflect the additional expenses paid by individual states (Rodríguez-Trejo 1998; Rodríguez-Trejo and Pyne 1999).

Within tropical Mexico, the fires affected all eight states in the south east and are estimated to have released 4.6 TgC through combustion in May and June 1998, burning approximatly 463 000ha, mostly along the common border region of Oaxaca, Chiapas and Veracruz. Tropical evergreen forests were among the most severely-affected land cover types (Cairns *et al*. 2000). In the 560 000 ha Chimalapas biological reserve, it is estimated that at least 35 per cent of the forests were damaged by fire, with 4 per cent being completely consumed. Left undisturbed, these forests will require a century or two to grow back (Ferriss 1999).

Since the fires of 1998, the Mexican government has made extensive efforts to improve its fire management programme. The annual budget for SEMARNAP was doubled to approximately US$20 million (Mutch *et al*. 1999) and investments in fire prevention and preparedness have been increased to match. SEMARNAP has developed and made public specific goals

for fire prevention, detection and suppression activities to be carried out over the next few years (SEMARNAP 2000).

In the Chimalapas at the end of the 1998 fire season, it was evident that the Mexican Government wanted actively to do something about the fire problem. More fire observation towers were built and fire brigades were better equipped. Overall fire management capability was improved through increased training, additional radio communication systems, and public information campaigns. The US Forest Service followed up the fires by giving safety training to people in areas where firefighters were killed (Ferriss 1999).

Nationally, Mexico took the unusual step of launching a post-fire campaign with a presidential decree in September 1998, known as the National Campaign for Ecological Recovery and Against Land Use Change. Its purpose was to prevent changes in land use in key areas affected by the fires. Initially the programme targeted roughly 200 000ha in 85 areas, spread across 21 of Mexico's 30 states. The criteria for site selection included:

- biodiversity richness;
- importance of the ecological services provided;
- extent of fire damage, and
- risk of change in land use.

Chimalapas was not included in the initial list of sites, but was expected to be added (Castilleja and Stedman-Edwards 1999).

The complexity involved in reforesting remote, species-rich, tropical forests has been considered a barrier to reforestation programmes (Ferriss 1999).

The need to change public attitudes and fire practices was illustrated by an assessment of the causes of the 1998 fires. The preliminary assessment by SEMARNAP indicated that almost all fires in natural vegetation were anthropogenic in origin. The reported causes of the fires showed that 54 per cent were attributable to agricultural activities, 16 per cent were deliberately started to promote a change in land-use designation, and 30 per cent were blamed on vandalism or accidents with cigarettes, camp fires and other ignition sources (Castilleja and Stedman-Edwards 1999).

The forest law of Mexico prohibits change in use of areas covered by mature tropical forest. However, local people often eliminate the forest by "accidental" fire so that they can have access to the land. The forest law (Codigo Penal, Art. 418) expressly forbids such activity (the penalty for intentionally setting forest fires is up to six years in jail without bail), but enforcement of this provision has proved difficult. In the central Mexican state of Mexico, of the 3 649 fires reported in 1998, only one resulted in prosecution. Local tolerance of fire use and the public's hostile reaction to the law's enforcement have reduced its effectiveness (Castilleja and Stedman-Edwards 1999).

One of the more interesting footnotes regarding the fires of 1998 has to do with community forests. In Mexico, approximately 80 per cent of the forests and wildlands are community property (*ejidos*). In forested areas that are being exploited commercially

by communities, local residents often promptly and effectively extinguished fires (Castilleja and Stedman-Edwards 1999).

In writing about the Mexican fires of 1998, Pyne (1998) observed that "The politics of fire is not unlike the ecology of swidden. The opportunities for change are greatest in the first year, drop significantly in the second year, and almost disappear by the third…."

The Mexican government seems to have taken this message to heart. It has worked to increase its prevention, detection and suppression capacity for fire (SEMARNAP 2000). Tools and maps for fire monitoring and predictive capacity have been improved and made easily accessible on the internet (http://fms.nofc.cfs.nrcan.gc.ca/mexico/index.html).

Additional lessons to be drawn from the 1998 fires include the obvious perverse effects of the forest law against conversion of mature forests to other land uses. The presidential decree of September 1998 to promote regeneration and prohibit land use change has been a step towards curbing these effects but laws are of little use if they cannot be enforced. The examples from community forests show the importance of valued local forests for spontaneous fire prevention and suppression efforts. Such valuation could include environmental services and not just the value of the wood. For example, nearly a third of Mexico City's water is supplied by a series of watersheds outside the Valley of Mexico (Castilleja and Stedman-Edwards 1999). If those forest communities could collect benefits from the environmental services the forests provide, there would be greater incentive for forest protection and reduced pressure for conversion to agriculture or logging (Chomitz *et al*. 1999).

As for the future, Mexico may not face another year like 1998 for a while, but there is no guarantee that such a year will not

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reoccur. A recent study (Mora and Hernández-Cárdenas 2000), showed that the unusually dry conditions of 1998 were not unprecedented in recent history. Of the last 20 years, only 1982 was comparable to 1998 in its nationwide drought conditions, but 1983, 1987, and 1988 all showed regionally-similar fire potential. The study also showed that forest fire occurrence was significantly tied to population density. Improvements in fire management and response capacity, and formalised agreements with countries such as the United States for rapid financial and technical assistance (Ferriss 1999), are a good start. Fundamental changes in social and economic conditions are needed. If not, these half measures will only delay the inevitable.

Brazil

The Roraima fires of 1998 actually began in 1997. The strong *El Niño* event caused an extensive drought. The region's desiccated vegetation allowed agricultural and savanna fires to develop freely in the State's forests. The fires began in August 1997 and went largely unreported until January 1998, when the Governor of Roraima declared a state of emergency (UNDAC 1998). They were not a complete surprise; in early September 1997, Brazil's National Congress set up an emergency committee to study the effects of *El Niño* and advise the government about prevention measures, after 4 335 forest fires had burned, even in tropical forests, in the state of Rio de Janeiro (Ferreira 1997).

The fires in Roraima were not the only fires in the Brazilian Amazon. The scale of the fire problem in the Amazon was evident as early as October 1997, when even the humid forests around Manaus began to burn out of control. Typical five-hectare agricultural fires spread to 200ha (CNN October 9 1997). By the end of the month, even the lake bed of the Balbina dam was on fire. The drought had lowered water levels so that previously-flooded forest was exposed. The dead trees dried and caught fire (Astor 1997). Smoke from fires throughout the region covered the 1.1 million residents of Manaus and resulted in a 40 per cent increase in respiratory problems (CNN October 9 1997).

As humidity levels in the Amazon reached their lowest levels since 1939, many fires spread out of control across the Amazon. Airports in the capital cities of Porto Velho, Rondonia and Rio Branco, Acre had to be closed down 20-30 times in September 1997 due to the heavy smoke (CNN October 9 1997). The State of Amazonas went an unprecedented 70 days without rain. Fires burned large areas in the Tapajos basin (Peres, 1999), southern Pará, and even in the relatively wet forests near Manaus, Amazonas (Nelson in press). By October, test fires showed that even intact primary forests near Paragominas Pará were not immune. In December, fires were burning in forests along both sides of a 40km section of highway (PA-150) south of the logging town of Tailândia, Pará (Cochrane and Schulze 1998).

In Roraima the fires worsened throughout the rest of 1997. The United Nations offered assistance to the Brazilian Government in both November and December, but received no response from the Ministry of Environment (CNN March

21 1998). On January 22 1998, the Governor of Roraima declared a state of emergency and assumed emergency powers to combat the fires, by now out of control (UNDAC 1998). Roraima was poorly-equipped to do this, however, with only 80 firefighters and six trucks in a state roughly the size of Great Britain (CNN March 14, 1998). Throughout January, February and early March, there was only one captain and ten fire fighters available for fire suppression outside the cities (Mutch *et al*. 1999).

By mid-March, the fires were completely out of control and encroaching on the Yanomami Indian Reserve. Roraima's Governor, Neudo Campos, decided to hire a fleet of 22 Russian and US fire fighting helicopters from an oil company in Maturin, Venezuela. The federal government approved the US$2.4 million rental expense, but did not release the funds. Instead, the government resolved to send a military team of 50 jungle fire fighting specialists (BBC News 15 March 1998).

In the meantime, the fires had destroyed 12 000 head of cattle and threatened another 90 000. Thirty per cent of the region's crops (US$36 million) were destroyed and 15 Yanomami Indian villages were threatened. Across Roraima, a smoke cloud, 300 kilometres in diameter, blotted out the sun during the day, while, conversely, flames lit the night sky (CNN March 14 1998 and BBC News March 15 1998). Winds of 35km per hour continued to push fires toward sensitive ecological reservations. The governor ordered emergency food provisions from other states to make up for the food shortfall caused by destruction of 80 per cent of the region's rice, bean and corn crops. An additional, US$3 million was spent for firefighters and army personnel to dig wells and create 6 000 small reservoirs in the parched countryside to support rural populations and fire fighting efforts (Kyodo News Service March 14 1998; Associated Press March 17 1998).

By March 20 1998, a 400km fire line was advancing westward into previously undisturbed forest. Several Yanomami villages were destroyed and an estimated 15 000 families lost their crops and livelihoods. At this point, Argentina pledged to send 100 fire fighters and four helicopters to help with relief efforts. The Venezuelan government

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started drawing up contingency plans to assist Brazil as the fires moved to within 50km of the border (BBC News March 20 1998). Meanwhile, the Brazilian government made plans to send another 300 firefighters to augment the 200 already battling blazes in the state (Brown 1998).

As in Mexico, the fire fighting forces in Roraima, had difficulties dealing with the peculiarities of fires in tropical forests. As hundreds of new firefighters arrived in the Amazon, they were often amazed to see wild animals running down roads to escape the fires. Many were concerned about being bitten by poisonous snakes (Brown 1998). Flames were everywhere and from time to time they would shoot up a palm tree and cause it to burst into flames (BBC News 23 March 1998). To reach many of the more remote fires, the firefighters had to trek up to 50km with heavy equipment or abseil from helicopters in order to clear landing spots. The temperatures near the fires were 50°C and humidity levels dropped below 30 per cent. The poorly-equipped forces used water containers, mops, sticks and flappers (shovel-sized flyswatters) to beat out flames. In addition, thick forest cover made tracking fire progress from the air difficult. Even when the fires could be located, the dense forest canopy prevented helicopters from dropping water on to them. Where fires were contained, actually putting them out required lengthy tree-by-tree examination to check for smouldering remains, often within the hollow centres of the trunks (BBC News March 21 1998). The 700-1 000 active firefighters who would eventually try to combat the flames were overwhelmed by a situation estimated to require 10 000 or more dedicated firefighters (Mutch *et al*. 1999).

By March 21, 120 Argentinian firefighters and four helicopters equipped with 500-litre water buckets had arrived in Roraima, and 100 Venezuelan firefighters were on their way to the northern Roraima border. Fires began to devastate the Maraca Ecological Station and the Niquia National Park. Firefighters tried to control the main fire focal points, but were overwhelmed by up to 2 000 separate fires. Brigade commanders estimated that they could control fires in some areas within two weeks, but that post-fire mop up operations to prevent reignition would take another ten days, or more (CNN March 21 1998).

On March 25, the Brazilian government accepted the offer of help from the United Nations. In Roraima, state officials reported that one large blaze near the community of Apiau had been put out, but that another 1 000 fires were still burning in the area (BBC News, March 25 1998). On March 27 1998, the Brazilian government made an official request to the United Nations for assistance with combatting fires in Roraima. The United Nations mobilised a disaster evaluation and coordination team the same day (UNDAC 1998).

Just as the team of United Nations experts were due to arrive in Roraima to assess the situation and determine the level of international assistance that would be required, the first significant rainfall in six months began to fall. The rains started hours after two Caiapo Indian shamans from the Xingu reservation, who had been flown to the Yanomami reservation, finished performing a ritual that was supposed to bring rain (CNN March 31 1998a; BBC News April 1 1998). The rains put out

many of the fires, but the 1 500 fire fighters continued to battle blazes with the help of Yanomami Indians (CNN March 31 1998b). Satellite images showed a 220km line of fire continuing to move southward into the forest (BBC News March 31 1998).

Continued rains in early April finally subdued the last of the fires (Cochrane and Schulze 1998). Initial estimates, indicating that the Roraima fires had burned an area of over 3 300 000ha, including an estimated 1 000 000ha of intact forest (Barbosa 1998), were disputed by the government. However, subsequent detailed studies of the area increased the estimate of the area burned to 3 814 400 - 4 067 800ha of savanna and 1 139 400 - 1 392 800ha of intact primary forest (Barbosa and Fearnside 1999). An independent study of Landsat TM imagery determined that an estimated 1 173 000 ha of forest had been impacted by fire with 25 per cent of fires occurring in areas of dense, closed canopy forest, while the other fires burned in open canopy forests of savanna-forest contact regions (Shimabukuro *et al*. 2000). Statewide, the fires had impacted 2.5 - 3.1 per cent of closed canopy forests, 17.5 - 21.4 per cent of open canopy forests, 38.3 per cent of savanna and 48.1 per cent of all rural landholdings (Barbosa and Fearnside 2000).

The fires had various impacts on forests across the region. Field studies conducted shortly after the fires showed that they had touched between 28 per cent and 78 per cent of the standing trees in affected areas and had killed between five per cent and 28 per cent of all contacted trees larger than 10cm in diameter at breast height (Nascimento *et al*. 2000). These numbers tally with mortality rates reported from other Amazonian sites shortly after forest fires (Peres 1999; Barbosa and Fearnside 2000) although these estimates are likely to be conservative, since many additional fire-damaged trees are likely to die over the first year (Holdsworth and Uhl 1997; Cochrane and Schulze 1999). Significant additional mortality, caused by falling trees, may occur for more than two years after the fire (Cochrane *et al*. 1999). Carbon emissions from the limited damage estimates of the Roraima fires of 1998 alone indicate that as much as 20 million metric tons of carbon was released to the atmosphere. Another 22 million metric tons will be released over the next several years by the decaying dead trees (Barbosa and Fearnside 2000). Huge stretches of damaged forests remain, which will not need *El Niño*-spawned droughts to burn again (Cochrane and Schulze 1999). Future fires will be more severe, due to the build-up of fuels caused by the trees burnt in the first fire (Cochrane *et al*. 1999; Cochrane 2000).

Lessons learned from Roraima

Based on interviews with firefighters (*bombeiros*) who participated in the effort to quell the Roraima fires in 1998, the following lessons were learned. (The list is taken directly from Mutch *et al*. (1999).

Positive elements

- *Bombeiros* with previous wildland fire training were especially effective in dealing with this complex situation.

- Even though there weren't any prearranged agreements, many agencies and organizations integrated their activities in a positive way, including

Roraima's state government, Army, Air Force, bombeiros (firefighters), Instituto Brasiliero do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Civil Defence, Meteorological Service, Argentina and Venezuela. Air Operations training at the National Interagency Fire Center in Boise, Idaho, was helpful in the coordination of air operations on the fires.

- The Incident Command System (ICS) for fulfilling command and control functions on the fires worked well, considering no prior arrangements were made for this system to be used by all agencies. The Governor and Army General in charge in Roraima were supportive of the ICS process.

- It was very useful that IBAMA in Brasilia (PREVFOGO) requested that *bombeiros* with wildland fire experience conduct a fire assessment in Roraima to describe the situation and recommend necessary fire suppression actions. Captain Gilberto Mendes and Captain Wanius de Amorim from Rio de Janeiro, along with Giovanni Cornacchia of PREVFOGO, conducted this assessment from March 15 to March 23. They flew a reconnaissance over 400km, mapping the location and extent of the fires with GPS and comparing locations with satellite images of the fires. Eventually, a good map was developed that clearly showed the serious extent of the fire problems. It was used by the Governor with their assessment report to request emergency funds from Brasilia. who initially released $1.5 million reais for fire fighting and support.

- The Army did an excellent job in providing logistical support for the firefighters, including tents, food, transportation, etc.

- Helicopters from Minas Gerais and Venezuela worked especially well on the forest fires due to prior experience. Pilots would benefit from special training in the use of helicopters on wildland fires.

- The *bombeiros* from Rio de Janeiro came fully equipped to be a self-sustaining fire fighting unit, requiring little in the way of outside support. On the C-130s that transported them, they brought a van, fire fighting engine, hand tools, ten new chain saws, tents, five GPS units, headlamps, batteries, first aid kits, a doctor, and radios.

- There was an efficient mobilisation with the C-130's once the order was received to go to Roraima.

- Daily operation plans were developed by some units to direct actions and provide necessary information for others.

Specific problems

- Outside resources were not mobilised quickly enough to reach the fires early and keep them small. The situation was overwhelming by the time *bombeiros* arrived from other States. *Bombeiros* worked hard under these difficult circumstances, but it was the rain in March, that prevented the situation from becoming much worse.

- There was no integrated communication system. Each organization had its own

internal communication system, but the different organizations needed to talk to each other on a single radio with multiple channels to cover all frequencies. There was no effective communication link between the Area Command Centre in Boa Vista and the field Command Centres.

- *Bombeiros* did not have the right type of equipment – or enough of it - for rain forest conditions.

- There were not enough fire fighters to deal with the prevailing conditions in Roraima. Although 700-1 000 people were engaged in the fire fighting operations, it was estimated that 10 000 or more fire fighters were needed by mid-March – the fires had been burning since January. A smaller number of trained and well-equipped fire fighters arriving in January and February could have greatly reduced the severity of the impacts and the costs.

- Many more fire fighters need to receive wildland fire training prior to the fire season, including *bombeiros* in the Amazon region, whose training is geared to structural fire fighting: fighting (i.e. fires in buildings). Volunteer brigades at local level also need to be equipped and trained to be able to respond immediately to fire emergencies.

- Air support was not continuously available to meet the needs of fire fighters on the ground. The military diverted helicopters to missions other than the support of fire fighters.

- Farmers kept burning even during the burning ban, until they were threatened with arrest. (Note: The Yanomami tribe, on the other hand, said they would not burn until allowed to do so by the *bombeiros*).

- The Command Centre in Boa Vista tried to produce daily plans, but the planning process tended to report what had occurred rather than direct priorities for future operations to guide field commanders. More experience and training in the ICS process would help. ICS positions within Command Centres should be filled by people with knowledge of fire-fighting operations and not based on their military rank.

- Daily evaluations should be set up and conducted to ensure that fire fighters are meeting incident objectives.

Fire Prevention Tools

Fire prevention is vital in any fire management strategy. It is generally much less expensive than fire suppression and reduces the costs of fire damage.

People need to understand why forest fires are a problem for them. The local population – whose land-use is extremely fire-dependent - must be involved, regardless of the number of trained fire fighters (Troensegaard 1990). Fire prevention campaigns will need to be tailored in individual cultures and communities. Despite local variation, however, prevention has some universal qualities. First, the message has to be effectively transmitted to the population. For fire prevention efforts to be successful in the tropics they will need to change the current cultural indifference to the fire. This will require sustained and varied campaigns to educate and shape rural ideas of fire. To be most effective, such programmes should be conducted throughout the region's school systems. While the goal is to rapidly increase fire prevention efforts, training the next generation in responsible fire management will likely to pay the most dividends.

The message to be conveyed needs to resonate with the populace. The people, whose ideas about fires are to be influenced, need to understand why forest fires are a problem for them. Specific examples need to be given of the problems of fires and they need to be put into a human context. Situations such as the Roraima fires of 1997-1998 in Brazil and the widespread fires in Mexico and Central AMerica would undoubtedly provide excellent examples.

Fire prevention messages need to be presented in varied ways and through all media possible including radio, television, print, posters, etc. Such messages benefit from slogans that can remind the populace of why fire prevention is important. One example is a slogan from 1903 in the United States that ran "One Tree Can Make A Million Matches - One Match Can Destroy A Million Trees".

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In general, simple emotional pictures are more effective than complicated messages. Posters and television are an ideal medium for this. Youth groups centred on the concept of fire prevention and environmental stewardship, together with memorabilia and awards, have been effective.

One study of the effectiveness of fire prevention measures found that a 20 per cent increase in funds for prevention reduced overall expenditure on fire management by 80 per cent (Pyne 1982). The transmission of proper burning practices through local radio programmes has been shown to be effective in reducing fires by local people in Guinea, West Africa (Brown 1998).

In Honduras the integration of technical experts into local communities has helped a great deal. Specific activities have included public meetings, courses and seminars for rural schoolteachers and the fostering of forestry clubs. Emphasis has been placed on improving information about forest fires in primary and secondary school curricula (Salazar 1990).

Fire prevention efforts should include the formation of local volunteer firefighting brigades, including women and even children, at all levels of society, and not simply by the government. In Brazil, the Amazon Working Group (GTA), a network of over 300 organisations, conducted a large-scale programme of field courses in 1998 that encouraged farm community leaders to form fire brigades in their communities (Nepstad *et al*. 1999b). This illustrates an effective way of making use of existing organisations to forward new messages. In general, extension agencies should provide technical training and support for responsible fire management.

Fire prevention methods are quite straightforward and well-known. They include:

- the creation of firebreaks, by clearing the ground of all fuels, around any area that is to be burned;
- the use of back or perimeter fires so that firebreaks are created by burning towards the centre instead of towards an edge;
- the cutting of dead trees which could span firebreaks as they fall and burn;
- consulting with neighbours before burning lands, and
- monitoring the progression and spread of fires.

All these fire prevention efforts can be expensive for local owners In many cases, financial incentives for effective fire management may be more effective than punitive legislation (Nepstad *et al* 1999b). Costa Rica's programme to compensate landowners for protecting the environmental services that their forests provide could be a model for Latin America (Chomitz *et al*. 1999).

It is well understood that prevention efforts are a cost-effective way of dealling with fire. Fire statistics for many countries are often unavailable, inaccurate or non-existent. Data that do exist indicate that human activity may cause 97 per cent of all fires (Rodriguez-Trejo and Pyne 1999) and that the vast majority of forest fires

result from escaped fires from pastures and agricultural lands (Rodriguez-Trejo and Briseño 1992; Rodriguez-Trejo and Pyne 1999; Mutch *et al*. 1999).

It is very difficult, if not impossible, to measure prevention efforts going on in several countries. In Mesoamerica for example, Mexico's Secretary of the Environment, Natural Resources, and Fisheries (SEMARNAP) is responsible for fire prevention, preparedness and suppression. Each state office is autonomous and responsible for maintaining its own fire programmes. In Costa Rica, legislation was passed in 1986 and 1996 to strengthen forestry laws against fire. This has resulted in the formation of regional and local fire management committees and volunteer fire fighting brigades.

Guatemala receives significant amounts of international assistance due to interest in Mayan ruins, but there is no national authority for fire suppression. Each region is responsible for dealing with its own fire problems. International emergency management training was especially effective in increasing fire awareness and response efficiency in the Petén region (Mutch *et al*. 1999). A review of forestry policies from 28 countries and territories in the Caribbean region (including parts of Central and South America) showed only one (Bahamas) with an explicit fire control plan (FAO 1998).

Within tropical South America, the Ministry of Environment and Renewable Natural Resources is responsible for coordinating Venezuela's fire prevention and response activities. Prevention efforts vary regionally but include the use of economic incentives for the prevention and control of wildfires.

In Brazil, the national fire management programme (PREVFOGO) is administrated by IBAMA's Directorate of Control and Supervision within the Ministry of Environment. It concentrates on:

- administering rural extension and education programmes with farmers to reduce the number of wildfires caused by agricultural burning;
- developing fire management plans for IBAMA's Conservation Units to use suppression and prescribed fire to minimise adverse impacts on ecosystems;
- monitoring hot spots by satellite to provide information on problem areas;
- providing training in fire prevention and firefighting, aerial firefighting methods for pilots, and fire cause determination, and
- preparing brigades to prevent and fight wildfires in Conservation Units and work with enforcement authorities to ensure that regulations are being met (Cornacchia and Pedreira 1998 as cited by Mutch *et al*. 1999).

Brazil also began a focused fire management programme for the Arc of Deforestation in the Amazon. This is a region approximately 3 000km by 600km, which covers the eastern and southern portions of the Brazilian Amazon. The project, PROARCO, was funded by a $15 million grant to the Brazilian government from the World Bank on 10 September 1998. PROARCO has the following components: monitoring agricultural burning and forest

fires (including the monitoring of fire risk); enforcing regulations regarding the use of fire in land management; preventing forest fires (including the training of farmers to use appropriate precautions and safeguards when burning); combating forest fires; and establishing a strategic task force, providing overall coordination (Mutch *et al*. 1999).

Landscape Zoning and Land Use Planning

Zoning of land use across tropical landscapes could be an effective fire prevention measure. For example, the disassociation of fire-maintained agricultural areas from selectively-logged forest would reduce the probability of forest fires and the severity of fire damage from accidental fires: easily-flammable fuel sources (e.g. selectively-logged forests) would not be exposed to frequent ignition events (e.g. pasture maintenance or new slash fires).

Physical division of land use may not be economically feasible. The economic returns from logging can be planned as a trade-off between potential profits and the extraction, transport and processing costs involved (Stone 1998). This means that, without market modifiers, logging will occur in forests that are most easily accessible. The ongoing settlement process in much of the tropics relies on roads and deforestation, both of which make more forests easily accessible to loggers. Furthermore, landowners often use logging on their lands to finance new deforestation.

A preliminary attempt to provide zoning criteria for the logging sector of the eastern Amazon was made by Veríssimo *et al*. (1998). Their recommendations were based on both economic and conservation considerations and made use of a multi-datalayer GIS model. Fire protection is an integral part of integrating selective logging and fire-dependent agriculture. In a synthesis of the ecology and economics of selective logging in tropical forests, Uhl *et al*. (1997) recommended that selectively-logged forests be protected from fire by a

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five-metre-wide firebreak for at least 10 years after timber extraction. Land use intensification has been cited as a way to increase land values and possibly decrease deforestation (Uhl *et al*. 1997). This would also help the fire problem because greater productivity and value of property would make fire prevention and protection efforts more cost-effective.

Fire Management Tools

Knowing what's going on

It is important to know where, when, why and how much is burning. By keeping track of such statistics it is possible to evaluate year to year variations in fire occurrence. This knowledge is necessary for multiple reasons. First, keeping track of both the timing and location of fires highlights the regions likely to have problems with fire and allows the most effective distribution of limited equipment and personnel. Second, leaning the reasons for individual fires provides information about their causes and also allows targeting of fire prevention measures. Keeping track of the number and cause of fire ignitions is a part of judging the effectiveness of fire prevention efforts to be assessed. Third, keeping track of the size distribution of burns and of the affected vegetation allows for evaluation of fire suppression measures. One commonly used statistic for evaluating fire suppression efforts is average fire size from year to year (calculated as total area burned/ total number of fires). It is important to know which areas have been affected by fire, particularly for tropical evergreen forests, because previous fire occurrence affects subsequent fire susceptibility and severity (Cochrane and Schulze 1999; Cochrane *et al*. 1999). Past fires affect a region's fire risk and need to be accounted for in fire hazard maps.

To judge the effectiveness of an overall fire prevention management programme an accurate and regularly-maintained database of fires that have occurred is necessary. Fires larger than 100-200ha are usually mapped, while those smaller are referenced by point coordinates. The type and quality of fire maps can vary depending on the importance assigned to a given fire or forest. Options include aerial sketch mapping, helicopter GPS mapping and airborne thermal line scanning (Lee *et al*. 2000). In remote regions with limited resources, satellite mapping of burned forests may be the only reasonable option. Linear spectral mixture modelling of Landsat TM imagery (Cochrane and Souza Jr. 1998) and ERS-2 Synthetic Aperture Radar (SAR) images have been shown to be useful for mapping tropical evergreen forests affected by fire (Siegert and Ruecker 2000). In practice, AVHRR imagery has been unreliable for mapping burned forests (Arino *et al*. 2000). The Moderate Resolution Imaging Spectroradiometer (MODIS) with its improved spatial (250m) and radiometric resolution in the visible and near-infrared bands may be a cost-effective and accurate way of estimating burn scars (Goldammer 1999).

Finding Forest Fires

To respond to forest fires in the tropics it must be possible to locate these fires while they are occurring. This is not just a matter of looking for the smoke. The culture of fire use in the tropics and the limitations of infrastructure and satellite technology make it harder to locate forest fires than it sounds.

In the tropics, fire is an important tool for land management. In addition to being used to clear new lands, fire is used to clear regrowth every two to three years (Fearnside 1990; Kauffman *et al*. 1998). Regardless of the presence or absence of forest fires, there will be tremendous amounts of fire across the landscape every year. It is not generally understood that the majority of fires detected each year are not actually deforestation or forest fires, but are simply maintenance fires in existing pastures (Miranda and John 2000). Not only do forest fires have to be detected, they also have to be distinguished from the thousands of intentional fires that are set each year.

Recognising or taking note of forest fires can be difficult even for local populations, who are accustomed to the annual fire season and the resultant pall of smoke that lasts for weeks, or even months, every year. This makes it difficult to distinguish forest fires from others. As fire is so common, even if extensive forest fires are alight, the local population may not consider them noteworthy. Fires set by landowners may not be legally sanctioned, and so not even they have an incentive to report escaped fires on their own properties. The infrastructure in many tropical frontier areas is such that there is often no readily-accessible method for communicating the existence of a fire. As many places are very remote and there is minimal government presence, people often don't know who or where to contact.

The use of either spotting towers or airplanes for fire location requires substantial infrastructure development and does not guarantee detection. Towers cover a limited area, and, in a complicated mosaic of forest, deforestation and pasture, observing personnel may not be able to distinguish forest fires from other fires across the landscape. Airplane detection is possible, but can be prohibitively expensive and limited by heavy smoke or clouds.

At present, and for the foreseeable future, satellite sensors are the tools of choice for fire detection in the tropics. Notable satellite sensor systems for fire detection have included the Advanced Very High Resolution Radiometer (AVHRR), Geostationary Operational Environmental Satellite (GOES) and the Defense Meteorological Satellite Program Operational Line Scanner (DMSP-OLS) satellites, even though all three were constructed for observing clouds and were never expected to be used in fire detection (Elvidge *et al*. 1999).

The AVHRR, GOES and DMSP-OLS sensors each have different strengths for fire detection. DMSP-OLS has a spatial resolution of 2.7km with the ability of limited data collection at 0.55km resolution.

In comparison tests between the sensors, DMSP-OLS had the highest per pass detection rate. However, DMSP-OLS data are only usable for night-time fire detection, allowing only one or two useable passes per day (Elvidge *et al*. 1999). Furthermore, the pixel smoothing used by the DMSP-OLS may count individual fires up to six times due to spatial overlap (Elvidge *et al*. 1996).

GOES, conversely, had the lowest detection per pass average, but the highest

overall chance of fire detection due to its being able to collect imagery every half hour. Unfortunately, for fire detection purposes, GOES has only a 4km spatial resolution (Elvidge *et al*. 1999). GOES products have been used to detect forest fires successfully in Central and South America (Prins and Menzel 1994; Alfaro *et al*. 1999). AVHRR's rate of fire detections per pass was between that of GOES and DMSP-OLS. AVHRR is capable of fire detection during daylight and can make four or more useable observations per day at a spatial resolution of 1km (Elvidge *et al*. 1999). AVHRR imagery has become the most widely-used data source for tropical fire detection and is incorporated into several monitoring projects. Examples include the Mexican (http://www.conabio.gob.mx/mapaservidor/incendios/puntos_calor.html) and Brazilian government sites (http://www.cptec.inpe.br/proucts/queimadas/queimap.html).

There are several limitations for using this satellite technology to detect fires in the tropics. First, there is the problem of scale. Even in the case of AVHRR, the highest resolution achievable is 1km, but land cover and land use can vary extensively over this scale. Therefore, within a single image, AVHRR cannot separate fires in forests from fires in agricultural lands. Furthermore, image registration problems of up to 3km between successive AVHRR images can lead to multiple counts of the same fire and misclassification (Arino *et al*. 2000). A recent workshop regarding the use of 1-km resolution AVHRR for fire detection concluded that the data provided by AVHRR are of very limited use. Specific problems cited included limited daily acquisitions (usually four per day), low geometric accuracy, misclassification of reflective soils and problems with cloud contamination.

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In general, AVHRR data is considered unsuitable for providing reliable estimates of fire activity and geographic extent of fire impact although the data is considered useful for providing general locations and timing of fire events (Eva and Gutman 2000).

Next there is the issue of detection algorithms. Simple temperature thresholds can be used to detect fires (Setzer and Pereira 1991) or contextual algorithms that compute relative thresholds based on statistics extracted from neighbouring pixels can be used to classify images (Flasse and Ceccato 1996; Justice *et al*. 1996). Threshold and contextual classifiers tend to detect different fires (Fuller and Fulk 2000). Within contextual classifications, different methods can lead to differing detection capabilities of different types and sizes of fires (Giglio *et al*. 1999). In fire detection, AVHRR imagery has particular difficulty with smaller cooler fires and larger hotter fires, due to detection threshold limits and sensor saturation.

Fireline intensity of tropical forest fires may be another confounding factor in fire detection. While there is no doubt that AVHRR and other satellites can be used to detect fires, there are no guarantees which fires will be detected. Deforestation fires can be very hot and may smoulder for as much as a week (Kauffman *et al*. 1998). However, fires in open vegetation types such as *cerrado*, and potentially pasture, may have low levels of detection due to the rate at which they burn and subsequently cool (Pereira Jr. and Setzer 1996). In the case of first time burns in forested areas, the fireline intensity, and hence the energy release, can be very low (<50kW/m) (Cochrane *et al*. 1999) and may not be detected by AVHRR detection algorithms. Detection is even less likely in newer contextual classifiers that often fail to identify less obvious fires. In cases where low intensity fires are widespread over a region, they can even influence the discrimination statistics of contextual classifiers in such a way that prevents detection of more intense fires that would normally be spotted (Giglio *et al*. 1999).

High resolution satellites including the Landsat Thematic Mapper (TM) and Système Probatoire pour l'Observation de la Terre (SPOT) can be used to detect fires but their relatively high cost, limited spatial and temporal sampling, and fragmented temporal archives limit their usefulness for active fire detection (Giglio *et al*. 1999). This problem is exacerbated in the tropics, where clouds and smoke can make the collection of useful imagery difficult. One multitemporal study of fire in tropical forests was only able to extract images from roughly every second year (Cochrane and Souza Jr. 1998). These data sources may be useful for mapping the locations where fires occurred, but will have limited usefulness in active fire detection.

Finding forest fires in tropical forests is very different from finding forest fires in temperate regions, where, tools such as AVHRR and spotting towers may be very useful, since a sudden hot spot on an image or plume of smoke on the horizon will frequently signify a fire that needs investigation. In the tropics, however, intentionally-set fires for land clearance and maintenance dominate the fire season. The problem that this

poses is illustrated by Brazil's attempts to use AVHRR for fire detection across its vast territory. Between July and November 1999, a total of 106 107 hot spots were detected. Enormous number of these were clustered in the southern and eastern Amazon, with many individual grid cells registering between 574 and 2 639 potential fires (Miranda and John 2000). Using AVHRR imagery to find fires in forests of temperate regions is like looking for stars in a clear night sky, while looking for fires in tropical forests is like looking up into the same sky when the clouds have covered it.

Human Resources

Any fire management programme requires trained fire fighting professionals. FAO has supported technical assistance for many fire mitigation projects throughout Latin America since at least 1970 (Troensegaard 1990). Such programmes, as well as exchange programmes between fire fighting professionals in several Latin American countries and the United States Forest Service, have helped to establish a core of trained fire fighters in many countries.

In Honduras, the mobilization of volunteer forces in conjunction with the United Nations World Food Programme (WFP), has been particularly effective. Food became an incentive for over 8 000 people to participate in forest conservation efforts. Integrating technical experts into local communities, providing informative meetings, training rural teachers and providing curriculum materials to schools regarding forest fire have all been effective in implementing an integrated fire management strategy (Salazar 1990).

Finding fire fighters

Even developed countries can suffer from a lack of trained fire fighters as was illustrated in the United States in the summer of 2000. The severe fire season required the assistance from fire fighters from Mexico, Canada, Australia and New Zealand (NIFC 15 August 2000) as well as several United States military units. Universities were asked to allow college students to remain on fire lines even as classes were beginning. Local people from fire affected areas and even spouses of forest department personnel were hired to assist in fire fighting efforts, but the lack of experienced 'crew bosses' was particularly debilitating. The United States Forest Service requested all employed personnel, regardless of job position, to volunteer to assist in fire fighting operations. To augment the lack of experienced personnel, many former fire fighters were even asked to return to service from retirement.

Private sector involvement can contribute to core fire fighting groups. In Chile, where plantation forestry is an important part of the timber industry, the government made private industries responsible for dealing with fires on their own lands. Market forces have resulted in the formation of well-trained and equipped, privately-supported, fire fighting brigades (Haltenhoff 1999). Despite the importance of training fire fighting professionals, it has been clearly established that fire mitigation efforts, based solely on professional fire fighting forces and punitive legislation, are doomed to failure (Troensegaard 1990). Local populations must be involved in and supportive of fire mitigation efforts since they are the ones who set and manage the vast majority of all fires.

Infrastructure

Fire management requires infrastructure. The condition of everything from roads to telephones will affect the efficiency and speed of response to fire events. Also, there needs to be a system of control centres for coordinating fire management activities and storage centres for fire fighting equipment. Such centres need not be fully manned throughout the year but if the infrastructure is not in place then the speed and efficiency of fire fighting operations will be reduced.

Monitoring a region for fires can require the construction and maintenance of a system of observation towers for fire spotters, air bases for fire fighting aircraft and even antennae and data centres for downloading and processing satellite information.

Ideally, volunteer brigades should strengthen fire fighting and management efforts. The creation of such brigades requires planning and effective training. They should be known to the government and be able to contact and effectively communicate with government personnel responsible for fire management.

Communications are a key element of fire management. In many remote regions, fire response time could be improved by improving telephone access. Public telephones and information (radio, television, extension services) about how to contact authorities in case of fire would be extremely useful.

The improvement of the infrastructure of a region by building new roads or paving existing ones can exacerbate land cover change and fire problems. Such changes allow greater access to the forests and make activities such as selective logging economically viable in new regions (Stone 1998). Large-scale road building projects can rapidly result in enormous changes in land cover and land use (Laurance *et al*. 2001). Since the fire environment will change with the new development, the necessary infrastructure for good fire management should be put in place and upgraded as communities grow.

Coordinated Response

In fire suppression, the goal has to be to provide the most effective response quickly and cost- effectively. When the fire situation is severe multiple agencies or other fire fighting groups need coordinating. For agency interaction, clear communication and smooth integration an established

structure, common terminology, tactics, equipment and training among fire fighting forces are necessary. The Canadian Interagency Forest Fire Center (CIFFC) (http://www.ciffc.ca/) provides this service in Canada while the Australasian Fire Authorities Council (AFAC) (http://www.ausfire.com/) integrates emergency responses for Australia, New Zealand and Hong Kong. The National Interagency Fire Centre (http://www.nifc.gov/) in the United States is a good example of what can be achieved.

The National Interagency Fire Center (NIFC), located in Boise, Idaho, is the United States' support centre for wildland fire fighting. It is comprised of seven federal agencies, which include the Bureau of Indian Affairs, Bureau of Land Management, Forest Service, Fish and Wildlife Service, National Park Service, National Weather Service, and Office of Aircraft Services. Their goal is to work together to coordinate and support wildland fire and disaster operations.

When the national fire situation becomes severe, the MAC group is activated. This group consists of the directors of each of the federal wildland fire fighting agencies, who are located at NIFC. Sometimes representatives from the General Services Administration, the US military, and state forestry groups participate. Depending on the national fire situation, the MAC group helps set priorities for critical, and potentially scarce, equipment, supplies and personnel. The federal agencies of NIFC share fire fighting supplies, equipment and personnel. Partnerships with state, local and rural agencies enhance their fire fighting and disaster management. NIFC also has a mutual assistance agreement with Canada and called on the assistance of Mexico, Australia and New Zealand in the 2000 fire season. The NIFC provides support to other nations when their services are requested by the State Department's Office of Foreign Disaster Assistance.

The federal agencies at NIFC and the National Association of State Foresters are members of the National Wildfire

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Coordinating Group (NWCG). The Secretaries of the Interior and Agriculture, created this group in 1976 to facilitate the development of common practices, standards, and training.

Similar entities need to be put in place throughout Latin America and the Caribbean, since no single nation has the human, material, or financial resources to cope alone during severe fire situations. The coordinating entities for fire fighting in these countries should set up formal Memoranda of Understanding. Furthermore, interaction and personnel exchange/training programmes should be fostered by international agencies. The countries of Latin America and the Caribbean should also work to develop interchangeable equipment, as well as common standards, practices and training.

Fire Prediction Tools

Early Warning Tools

Early warning systems are essential components of a fire management system. Ideally, they integrate information about weather, vegetation dryness, fire detection and fire spread to provide a simple measure of the fire situation. Depending on the complexity of the system, the index may incorporate information on vegetation cover, values at risk, and model results for fire occurrence and behaviour (Goldammer 1999).

Fire Risk Assessment

Being able to assess the potential of a fire to start or spread is central to a fire management programme. Many components such as weather, climate and fuel conditions combine to give a comprehensive picture of current fire risk across the landscape.

Monitoring Fire Weather

To understand the fire situation in a region, current weather conditions must be known. In typical weather monitoring systems, maps are made based on daily reports from all weather stations. Readings are usually from noon or early afternoon and include such information as average wind speed and direction, 24-hour rainfall totals, temperature, relative humidity, and dew point. The information from the various weather stations is interpolated from station positions to create maps of likely conditions across the nation or region of interest. Spatial accuracy of the resulting maps will be a direct reflection of the spatial density of weather stations.

The United States maintains 1 500 weather stations operating in its Weather Information Management System (WIMS) which can be viewed at http://www.fs.fed.us/land/wfas. Canada presents similar maps for its fire danger system on the internet (http://fms.nofc.cfs.nrcan.gc.ca/cwfis/index.html). In Latin America, Mexico's system can be viewed at http://fms.nofc.cfs.nrcan.gc.ca/mexico/index.html and Brazil's at http://www.cptec.inpe.br/products/queimadas/queimap.html.

The hierarchy of potential fire-weather-forecasting services (Reifsnyder 1978) includes:

- Fire-weather warnings: at the very minimum, a weather forecast office to provide fire-weather services should be able to issue forecasts of dry and/or windy conditions that may occur during fire seasons;

- Fire-danger forecasts: if a country's organisation responsible for fire management has an operational fire-danger-rating system, then fire-weather forecasts should include all the specific weather elements used in calculating the fire-danger rating. This may include special regional weather events, and

- On-site forecast services: in highly-developed fire-management agencies, a dedicated fire-weather unit may be required to operate at the site of existing or planned fires. The personnel can use mobile observation equipment to make local forecasts for the conditions in the immediate vicinity of the fire.

Dead Fuel Moisture

In order to predict if a fire can be ignited or will spread it is necessary to know the approximate fuel moisture content. Dead fuel moisture responds to ambient environmental conditions as a function of its size, shape and exposure. Fuels are typically divided up into 1-hr, 10-hr, 100-hr and 1 000-hr time lag classes based on diameter (0-0.62, 0.62-2.54, 2.54-7.62, >7.62 cm).

Fuel moisture calculations are made as follows:

1-hour:
Fine fuels. Respond quickly to weather changes. Moisture levels computed from observation time temperature, humidity and cloudiness;

10-hour:
Moisture computed based on observation time temperature, humidity and cloudiness;

100-hour:
Moisture levels computed from 24-hour average boundary condition composed of day length, hours of rain, and daily temperature/humidity ranges, and

1 000-hour:
Moisture levels computed from seven-day average boundary conditions composed of day length, hours of rain, and daily temperature/humidity ranges.

Live Fuel Moisture

In order to predict how green vegetation will contribute to a fire, it is important to know the live fuel moisture content. For fire prediction purposes this means leaf moisture. Live fuel moisture content is based on dry weight, and can commonly range from 50 to 250 per cent. Due to greater quantities of oil and resin in live fuels, they can become flammable at values below 120 per cent and fire crowning is likely at moisture values below 100 per cent (Agee 1998).

Relative Greenness

Relative greenness is derived from the Normalised Difference Vegetation Index (NDVI) (Goward *et al*. 1990) which is calculated from data obtained by the Advanced Very High Resolution Radiometer (AVHRR). The basis for calculating relative greeness is historical NDVI data (1989 to the present) that defines the maximum and minimum NDVI values observed for each pixel. Thus relative greeness (RG) indicates how green each pixel currently is in relation to the range of historical NDVI observations for it. RG values are scaled from 0 to 100, with low values indicating that vegetation is at or near its minimum greenness.

Specifically the algorithm is:

RG = (NDo - NDmn) / (NDmx - Ndmn) x100.

The variables used are:

NDo = highest observed NDVI value for the one-week composite period;

NDmn = historical minimum NDVI value for a given pixel, and

NDmx = historical maximum NDVI value for a given pixel.

The purpose of using relative greenness is to define the proportion of live and dead vegetation. Since it is based on AVHRR data the relative greeness map has a 1km resolution (Burgan *et al*. 1998).

NDVI maps for tropical evergreen forests may be of limited value since values tend to saturate at Leaf Area Indices (LAI) above four. Typical LAI values in tropical evergreen forests are often five to six.

Drought Maps

Drought indices account for imbalances in water flux over periods of days, weeks or even years. At its simplest such an index is a balance sheet between total precipitation and total evapotranspiration over a period of time. The Keetch-Byram Drought Index (KBDI) is one that is commonly used. The basis of the measure is the relative moisture deficiency created in deep duff or upper soil layers when evapotranspiration exceeds precipitation. The drought index provides a numerical value related to the flammability of organic material in the ground. The index is calculated based on maximum daily temperature, daily precipitation, previous precipitation and annual precipitation and tied to an assumed soil capacity of 20cm. The KBDI is normally presented as a range from 0 to 800 (Keetch and Byram 1968) but would equivalently be 0 to 2000 in metric units. The values can be roughly interpreted as follows:

KBDI= 0-200 (0-500): Soil moisture and large class fuel moistures are high and do not contribute much to fire intensity;

KBDI= 200-400 (500-1 000): Lower litter and duff layers are drying and beginning to contribute to fire intensity;

KBDI= 400-600 (1 000-1 500): Lower litter and duff layers actively contribute to fire intensity and will burn actively, and

KBDI= 600-800 (1 500-2 000): Often associated with severe drought and increased wildfire occurrence. Intense, deep-burning fires with significant downwind spotting can be expected. Live fuels can also be expected to burn actively at these levels.

Indices such as the Keetch-Byram Drought Index may not be completely appropriate for tropical evergreen forests due to their deep-rooting capacity. A preliminary water balance model for Amazonian forests which uses soil depths to 10m is being tested (Nepstad *et al*. 1999). As of yet, there is no definitive index associated with the map generated with this model.

Fire Danger Maps

Fire danger maps are the compilation of information on current and antecedent weather, fuel types and the state of both

live and dead fuel moisture. These maps integrate the data from various other maps and ancillary information (e.g. fuel type, levels of fire combating capacity including manpower, etc.) to provide an index of potential fire risk or severity. One index, which has been used in Australia, is the McArthur Fire Danger Index (Loane and Gould 1986). In the United States this takes the form of the National Fire Danger Rating System (NFDRS). The Canadian version is the Canadian Forest Fire Behavior Prediction System (FBP) (Hirsch 1996).

Fire Hazard Mapping

In order to evaluate the fire situation, it is necessary to know the risk of fire occurrence as well as what is actually at risk. Prevention efforts can be targeted for areas which have a high risk of fire, while suppression efforts can be concentrated where fires threaten regions of particular value or importance. Keeping track of the quantity and status of potential fuels across the landscape is key to this process.

In the case of disturbed forests (e.g. logged or previously burned) and agricultural systems, a simple measure of the number of consecutive days without rain can be used to predict fire susceptibility (Uhl and Kauffman 1990; Holdsworth and Uhl 1997; Cochrane and Schulze 1999). For undisturbed forests interiors, a drought index should be used to predict fire risk. Indices analogous to the Keetch-Byram index should be employed in the tropics. Such information will not be sufficient for predicting fire risk in all forests but, in the case of tropical evergreen forests, it will allow fire managers to predict when undisturbed forests can burn. Such knowledge is necessary for predicting when the conditions exist for very large-scale fires, such as those that occurred in Roraima, Brazil and southern Mexico in 1998.

In tropical regions it will be important to know the status and distribution of land cover. This entails the generation of reasonably accurate and current maps of the changing landscape. It is important to know where the people are and for what crops or other activities the land is being used. Furthermore, it is important to know where deforestation and logging are occurring. Though deforestation is readily apparent on satellite imagery the damages from selective logging have been hard to detect. Techniques for the detection of selective logging (Souza Jr. and Barreto 2000) have been recently developed and applied to areas as large as the Brazilian Amazon (Janeczek 1999). In Brazil, a line scanner and a digital camera, mounted on a Brazilian Air Force Lear jet, have been used to map successfully selective logging and deforestation in Amazonia (Sandberg 1998). Land cover maps should also include any forested areas known to have burned.

Land cover maps can be used as a resource for both fire prevention and suppression efforts. For example, in areas where new deforestation or pasture maintenance fires are planned, the proximity and status of forests can be taken into account when determining the required amount of fire prevention effort. If planned burning is going to occur near the vicinity of either logged or previously-burned forests, then extra fire precautions can be required. Conversely, a land cover map can assist fire suppression efforts by illustrating the areas at risk. With limited

fire suppression resources, for example, a fire coordinator could choose which endangered perennial crops or plantations to protect over pasture land, or to prevent a fire from entering a large area of logged forests. Land cover maps are an information resource that can help professionals to manage fire better across the landscape.

Fire Detection and Monitoring Tools

Fire detection and monitoring is an essential part of fire management. At its simplest, active fire monitoring can be accomplished by systematically patrolling a region. In many cases patrols are backed up by dedicated fire observation towers. These are usually placed so as to take advantage of local topography (e.g. hills and ridges). Personnel monitoring a region for possible fires will usually have equipment to determine the direction and approximate distance to any smoke plumes spotted. Communications equipment is also necessary for the information to be relayed to a fire control centre. As far as they can, fire observation towers should provide interlocking fields of view so that more than one bearing can be taken on any individual fire. Local people, with little training, can man them.

The use of airplanes and helicopters for aerial detection of fires is another option and is especially useful for initial observations of fire conditions. Many aircraft can also suppress fires. The use of aircraft, however, is expensive and requires the construction of adequate infrastructure. Personnel to pilot and maintain the aircraft require substantial training. An example comparison of fire suppression costs for ground and air methods is given in Table 7 (Loane and Gould 1986). The values pertain to bush fires but they give an idea of the relative expenses of ground versus air suppression. It is noteworthy that in most developing countries manual labour costs will be much lower and aircraft maintenance costs correspondingly higher than in the table. Furthermore, air suppression costs are calculated based on the existence of a substantial amount of infrastructure including air bases within 40-60km of fires and readily-available water sources within 10-30km of all fires. Aerial suppression efficiency will be lower in tropical evergreen forests due to thick canopy and difficulty in seeing fire lines. Maximum utility and cost efficiency is likely to be gained by multi-use craft such as helicopters which can be used for detection, suppression and firefighter transport. Ground crews will generally be more cost-effective for suppression but aerial support can be effective in the initial response to more remote fires.

Among satellite systems, the AVHRR, GOES and DMSP-OLS sensors have different strengths for fire detection. DMSP-OLS has a spatial resolution of 2.7km but is limited to nighttime fire detection (Elvidge *et al*. 1999). Furthermore, the pixel-smoothing generally used by the DMSP-OLS may count individual fires up to six times due to spatial overlap (Elvidge *et al*. 1996) and lead to overcounting (Fuller and Fulk 2000). GOES, conversely, is able to collect imagery every half-hour. Unfortunately, for fire detection purposes, GOES has only a 4km pixel resolution (Elvidge *et al*. 1999). AVHRR is capable of fire detection during daylight and can make four or more useable observations per day at a spatial resolution of 1km (Elvidge *et al*. 1999).

Table 7. Comparative capabilities and costs for different fire suppression options.

Method of Fire Suppression									
	Ground Crew		Aircraft						
			Helicopters				Airplanes		
	Hand-tool crew	Machine crew	Bell 206 (water)	Bell 212 (retardant)	Thrush Commander (retardant)	Canadair CL-215 (water)	Grumman Tracker (retardant)	DC-6 (retardant)	Hercules MAFFS (retardant)
Fire-to-retardant distance (km)			6	10	25	25	75	150	150
Retardant tank volume (liters)		4 000	340	1 362	1 500	5 455	3 545	11 365	11 355
Net length of fire line per load (m)			71	217	166	135	241	490	460
Time between drops (min)			10.5	17.6	28.7	19	45.4	72.1	65.6
Rate of line construction (m/hr)	350	1 000	405	740	347	426	318	408	420
Relative cost * cost/hr	1.0	3.3	4.3	23.9	9.5	32.8	27.4	54.7	79.7
cost/m of fire line	1.0	1.1	3.6	11.2	9.7	26.7	30.0	46.7	66.1

Source: Adapted from Loane an Gould (1984).

Note: Hand-tool crews - six man, Machine crews - nine man with bulldozer, tanker and light support units. All comparison cost for air craft and ground crews include travel expenses to and from the site of the fire.

* Relative costs one based on information from loane and Gould (1984) which showed dollar amount per hour and meter of fire line using (1983) Australian dollars. Relative costs are calculated by dividing all original costs by the cost of hand tool crews in order to provide comparative rations (e.g. using a Bell 212 helicopter with retardant costs 23.9 times as much as a hard - tool crew per hour but only 11.2 times as much per meter of fire line).

In addition, the Tropical Rainfall Measuring Mission – Visible and Infrared Scanner (TRMM-VIRS) has recently been shown to be similar to AVHRR for fire detection purposes. The TRMM-VIRS imagery may be particularly useful for detecting unusually large or hot fires (Giglio *et al*. 2000).

Another new sensor with promise for fire detection and monitoring is the Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS has increased capabilities for coarse resolution imagery with 36 individual spectral bands between 0.4m and 14.3m at spatial resolutions of 250m to 1 000m. MODIS platforms should provide two to four passes per day and have increased saturation levels so that fire monitoring capabilities can be improved. In addition the improved spatial (250m) and radiometric resolution of MODIS in the visible and near-infrared bands will increase the accuracy of burn scar estimations (Goldammer 1999).

Future sensors for fire detection include BIRD and FOCUS (Goldammer 1999; Oertel *et al*. 2000). The Bi-Spectral Infrared Detection (BIRD) Mission will use a small satellite to test a new generation of infrared array sensors that provide better analysis capabilities for High Temperature Events (HTE). FOCUS will be flown on the International Space Station from 2003-2005 as an externally mounted payload for observing high latitudes (40 – 52. Both BIRD and FOCUS are expected to provide surface temperature, area, and geo-location of fires with a spatial accuracy of 300m. In addition, FOCUS is expected to provide:

- gas temperature;
- CO/CO_2 ratio as an indicator of combustion efficiency and fire type;
- column content of fire gases such as CO, NO, CH_4, H_2O, CO_2, $SO_{2;}$
- CH_4/CO, NO/CO_2 and aerosol/CO ratios, and
- temperature and humidity profiles, aerosol optical depth of smoke and larger plumes.

Fire fighting and Assessment Tools

Fire Behaviour and Propagation Models

FARSITE (Finney 1998) and BEHAVE (Burgan and Rothermel 1984, Andrews 1986, Andrews and Chase 1989), provide methods to simulate fire behaviour for areas up to several thousand hectares. BEHAVE is a combination of a fuel model and a fire behaviour prediction model. The programme is modular and can be used for a variety of tasks from real-time prediction of the behaviour of wildfires to initial attack dispatch of fire crews (Andrews 1986). Each module requires the input of ambient conditions (e.g. fuel model, fuel moisture, etc.) in order to output fire behaviour or fire response options. The BEHAVE model and literature are available from the US Forest Service. The BEHAVE Fire Behavior Prediction and Fuel Modeling system is currently being revised. The new model has expanded capabilities and is called the BehavePlus Fire Modeling System. The most recent information about BehavePlus can be found at http://fire.org/.

FARSITE incorporates existing models of surface fire, crown fire, point-source fire acceleration, spotting and fuel moisture. The model uses input data on elevation, slope, aspect, fuel model, canopy cover, crown height, crown base height and crown bulk density to parameterise and predict fire behaviour and two-dimensional fire spread (Finney 1998). FARSITE software and users' guide are available for download free of charge at http://www.montana.com/sem

Satellite Mapping of Forest Burning

It is critical to map the forests that burn in order to calculate fire statistics and gain a general understanding of how important fire disturbance is in a region. In developed countries, there are a number of options for mapping active fires and doing assessments. Fires larger than 100-200ha are usually mapped while those smaller than this are referenced by point coordinates.

The type and quality of fire maps will vary depending on the importance of the fire or forest but options include aerial sketch mapping, helicopter GPS mapping and airborne thermal line scanning (Lee *et al*. 2000). In remote areas, especially in developing countries where human and physical (e.g. airplanes) resources are scarce, satellite mapping of such events is desirable and necessary.

Determining which tropical forests have burned and where is not a simple exercise. Ideally, fires would be mapped by low-cost, frequently-collected satellite imagery. There are several algorithms that have attempted to estimate area burned from AVHRR imagery but burned scar assessments have proven difficult since the burned area attributable to a given hot spot cannot reliably be determined (Arino *et al*. 2000).

Burn scars in higher resolution imagery of tropical forests have been recognised and reported (e.g. Giri and Shrestha 2000). The burn scars are often very transient in the imagery however, due to rapid forest regeneration (Stone and Lefebrvre 1998). A subpixel linear spectral mixture modelling approach has been developed which can accurately locate and classify tropical forests which have been impacted based on the fraction of non-photosynthetic-vegetation (e.g. dead leaves, branches etc.) present (Cochrane and Souza Jr. 1998). The technique is limited to detecting fires that are one to two years old and has enabled assessments of fire impacts in on the integrated analysis of multiple images of the same region over several years (Cochrane *et al*. 1999). More recently, the efficacy of ERS-2 Synthetic Aperture Radar (SAR) images for mapping burn scars in tropical evergreen forests has been demonstrated (Siegert and Ruecker 2000). The method is somewhat confounded by moisture, so weather information from the study regions is crucial, and there is no information yet as to how long burn scars may be apparent in SAR imagery. However, SAR sampling occurs monthly and makes this a promising technique for periodic mapping of burn scars in tropical forests.

Data fusion techniques, combining information from active fire detection (e.g. AVHRR) with high resolution optical and SAR data may be the best way to determine burn scars using current technology (Arino *et al*. 2000). The need for high-sampling frequency using high-resolution imagery makes the mapping of forest fires in the tropics expensive and labour-intensive. Where possible, such work should be combined with ongoing land use and land cover classifications (e.g. deforestation, selective logging, forest regrowth etc). The need for up-to-date ancillary information to enhance the appropriate interpretation of fire information from satellite imagery has been previously noted (Jacques de Dixmude *et al*. 1999).

Staging Materials

It is important to have the fire fighting materials needed ready in the appropriate places during the fire season. The managers of the supplies need to be able roughly to predict how much material will be necessary, as well as where and when. There will be a certain amount of trial and error in the process, but in many places the information may already exist. In most

regions throughout Latin America, the fire season is well-defined and well-known, so, in smaller countries or management regions, this may be all that is necessary for planning purposes. In larger regions and countries that have differing climates and fire seasons across their expanse, this information will not be enough. Tools such as the historical database of AVHRR hot spots can be used to map the typical distribution of ignition events in both space and time on the landscape. Drought indices, land cover maps and fire weather information can further enhance this information by indicating the regions most susceptible to fires. Fire risk can be estimated by combining the historical information on where ignition events are likely to happen with knowledge of which forests are currently most vulnerable to fire. Fire fighting materials can then be ready in the regions perceived to have the greatest risk of fire. Predictions of fire risk can also be used to inform fire prevention efforts or to provide the basis for local bans on fire use.

The effectiveness of national fire programmes in developing countries has often been reduced by the cost and limited availability of fire fighting equipment. Even the most basic of fire fighting hand tools can become inordinately expensive when they must be imported from developed countries and paid for in foreign currency. Delays are another consideration. For a nation’s fire management programme to succeed, the development of local production capacity is crucial. It must become a priority for technical assistance to be given so that such tools can be made locally (Troensegaard 1990).

Materials should be ready in fire-prone regions to enable a rapid and effective response to fire events. This requires some ability to predict when and where fires are likely to occur so that decision-makers can allocate the limited numbers of trained fire fighters and special fire fighting equipment (e.g. helicopters and airplanes) for national fire response throughout the year.

Mopping Up

The logistics of fire management and coordinated responses to fire have been developed and honed to a fair degree by a number of countries (e.g. Canada, United States, Australia). Where possible, such knowledge should be adapted and applied to the tropical regions of developing countries, bearing in mind their physical and cultural realities.

Tropical priorities for any fire management programme must be prevention and education. Fire detection capabilities need to be able to locate fires and also discriminate between fires (such as those planned for land management) from those which have escaped and forest fires. Satellite detection can be especially effective in more remote areas if the local people are supportive

Finding fires in tropical forests, even when they are known to exist, can be difficult. The vegetation of tropical forests can be very dense and relatively impenetrable for ground forces unfamiliar with such forests. In many cases, especially when fire fighters from other regions are employed, there will be considerable fear of possible wildlife encounters and becoming disorientated or lost. There will be additional concerns about

insect-borne (e.g. malaria, dengue fever) and water-borne diseases (e.g. cholera, hepatitis). These are real possibilities and need to be borne in mind in training and contingency plans.

The use of aerial detection and suppression of fire in tropical forests can be critical but problematic. In regions with extensive clouds of smoke and few potential air bases, the usefulness of aerial forces will be most limited during the severest fire conditions. In many cases, detection from the air will be very effective, but such forces need to be able effectively to record positions and communicate with ground and coordinating entities. Additionally, trained forces need to be able to descend and penetrate the canopy in order to open landing sites for deployment and resupply of fire suppression ground forces. Aerial fire suppression efforts will often be hampered by the forest canopy, which can disperse smoke and obscure direct line of sight. Furthermore, the canopy will intercept much of the water or suppression agents.

For both aerial and ground suppression forces, water access can be a significant problem in fire combat operations. As was seen in Mexico and Roraima, fires in tropical evergreen forests are most likely to happen during periods of extensive drought when many wells, streams and other water sources will be dry. Substantial resources and time were devoted to developing accessible water sources in the fire suppression efforts in Roraima, Brazil.

Speed of response is critical. The fact that tropical forest fires spread relatively slowly should not lead to complacency. As the area that is burned grows, so does the chance of fires contacting large combustible fuels. Mopping-up operations are important after all fires, to make sure they do not re-ignite. In tropical forest this Is particularly important and can be time-consuming.

Fires can smoulder on for weeks or even months and spring up after all fires were thought to be out. Since fires in tropical forests tend to consume the litter layer of the forest and leave a discontinuous fuel base, it is tempting to believe that mopping-up operations need only to concentrate on downed logs and trees near the outer perimeter of where the fire burned and the unburned sections of forest nearby. This is a good initial response, but it is not sufficient. Even smouldering fuels far from other fuels sources can lead to re-ignition. Vegetative growth in tropical evergreen forests is often exuberant; foliage from trees killed in the initial fire can begin to blanket the ground with a new fuel layer within a few days (Cochrane *et al*. 1999). This process has resulted in as many as three fires in a single area within a given year (Cochrane and Schulze 1999) as fires sweep back and forth over re-accumulating litter layers. The only way to prevent this is to make a detailed search of the entire area, checking every downed log and each standing tree, with particular attention to potentially hollow trees, for evidence of smouldering. If a fire is rapidly contained, then the mop-up operation will be minimal, but if fires are allowed to burn over substantial areas of tropical evergreen forest, then mop-up time and manpower increases tremendously.

Conclusions

The fire situation is severe in many of tropical evergreen forests in Latin America and the Caribbean. The widespread fires of 1998 have changed the fire landscape by damaging vast forested areas next to fire-maintained human ecosystems. All these forests – like selectively-logged and hurricane-damaged forests - are at increased risk of recurrent fires over the next decade.

The landscape has a memory of sorts. Each year's forest degradation (logging, burning, fragmentation, natural events) is carried into the future Tropical landscapes change all the time from small fire-maintained plots in a sea of near-fire-proof forest to become increasingly interlinked, fire-vulnerable and fire-prone. This means that the fire situation in any human-inhabited location is likely to get worse each year. It is relatively easy to keep fires out of intact forests, but now that the process of encroachment into forests has begun it will be difficult to halt. Fire has a momentum in tropical evergreen forests. This is under-appreciated by resident populations, policy makers, fire managers and scientists.

Fire managers and policy makers have to deal with realities of fire in tropical evergreen forests. The problem for fire managers is that both fuel (e.g. logging debris, fire-damaged forests) and heat (e.g. ignition events, moisture reduction) are increasing across the landscape. In order to prevent the fire situation from deteriorating, it will be necessary to reduce the conjunction of heat and fuel, both spatially and temporally. The true key to this issue, whatever other measures are taken, is resident populations' concept of fire.

The fire problem needs to be tackled in many ways, from better education and fire management to economic incentives and land use planning, but the people that inhabit these regions have to be supportive of solutions.

The problem is severe but not impossible to deal with. If there is commitment on the part of governments and community leaders to educate and influence their people about fire and its prevention, then fire's growing influence in the forests of these regions can be reduced and nature can begin to help them to recover.

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Current Wildfire Response Capacity in the selected countries of Latin America and the Caribbean.

The current capacity for organized response to wildfire is very variable across Latin America. A summary of the known resources and organization of several countries in the region is provided below.

Chile

In Chile, government fire management activities are the responsibility of the National Forest Corporation (Corporación Nacional Forestal (CONAF)) within the Chilean Forest Service (Haltenhoff 1994). Private companies are responsible for fires on their own lands and maintain their own Prevention Programmes, fire brigades and equipment for fighting forest fires (Haltenhoff 1993). Private sector and federal government invest approximately $20 million per year in prevention, suppression and training efforts. Chile's human resources include a dedicated staff of 2 500 in its combined (private and federal) fire management programme. Additional fire fighting resources include (Mutch *et al* .1999):

- 30 operation centres;
- 209 observation towers;
- 187 prevention technicians;
- 151 fire fighting units (8 to 15 fire fighters per unit);
- 19 tanker trucks;
- 22 helitack crews (only 14 according to Haltenhoff 1999);
- 22 helicopters (only 20 according to Haltenhoff 1999);
- 14 air tankers, and
- 7 coordinating aircraft.

Costa Rica

After a number of large wildfires, Costa Rica developed a fire management programme based on 1986 legislation to discourage the use of uncontrolled fire. The legislation set fines for inappropriate fire use and was strengthened further in 1996. The fire management programme in Costa Rica is based on regional and local fire management committees. The committees are volunteers who receive professional and technical assistance from the government. Each committee is responsible for the prevention and suppression of fires in their region. The government is intent on decentralising fire management activities by providing economic incentives for provinces and local communities to become involved. The Central Government provides funding for tools, equipment, training and education and the National Security (Insurance) Institute provides additional funds for the programme. Fire fighting relies heavily on volunteer fire brigades (Mutch *et al*. 1999). In 1996, Costa Rica's forestry law (Law no. 7575) explicitly recognised four external environmental services provided by forests:

- carbon fixation;
- hydrological services;
- biodiversity protection, and
- the provision of scenic beauty.

Subsequent implementing laws in 1997 have been used to pay landowners for agreements to protect their forests (Chomitz *et al*. 1999) thereby providing an added incentiv for landowners to control and combat fire.

Cuba

The Forest Ranger Department (CGB) in the Ministry of the Interior has responsibility for the prevention, control and suppression of fire in Cuba. During periods of drought, most of CGB workers are dedicated to forest fire protection. Responsibilities include spreading information about fire risk to rural communities, and conducting ground patrols. In addition, Cuba has more than 30 Forest Fire Control Units, a year-round fire fighting force located in the highest risk regions. These units are well trained and equipped with communications gear, manual equipment and fire trucks. Observation towers, and, during the height of the fire season (February to May), AN-2 (Antonov) airplanes are used for fire detection. Aerial fire suppression is carried out as necessary with PZL-M18 (Dromader) airtankers. Ground forces are augmented with volunteer brigades as necessary (Rodriguez 2000).

Guatemala

Guatemala has no national authority for fire suppression. Fire management activities are decentralised: each region is responsible for fire prevention, preparedness and suppression. Initial response to fire comes from local volunteers or government personnel if the fire is on State lands. In severe fire situations, the regional governor assumes emergency management responsibility. The national civil defence agency only becomes involved if there is a presidential disaster declaration. Fire management activities in Guatemala rely on a high degree of international involvement. The use of specialised fire fighting tools is increasing (Mutch *et al*. 1999).

Honduras

The Honduran government established the Honduran Corporation for Forestry Development (COHDEFOR) in 1974 and charged it with forest-fire mitigation as one of its responsibilities. As of 1990, COHDEFOR had 43 management units that covered nine forest regions across the country. Each management unit consists of a ten-person squad, one to two observation towers, mobile fire wardens and voluntary fire fighting auxiliaries. COHDEFOR has an annual budget of approximately $3 million (1990 estimate). Fire fighting campaigns incorporate human resources from multiple sources into a force of over 11 000 people. COHDEFOR itself provides for 4 550 personnel, the United Nations World Food Programme (WFP) supports an additional 4 850 800 more come from agroforestry cooperatives, 550 from the armed forces, 350 from the timber industry and another 500 from elsewhere.

Mexico

Mexico has a well-trained and efficient fire fighting force. SEMARNAP maintains an extensive infrastructure and a large number of well-equipped fire –fighting brigades. Specific resources include:

- 64 observation towers;
- 150 fire brigades (400 more including municipal, volunteer, and state crews);
- 6 helicopters (4 contracted and 2 SEMARNAP);
- 2 detection aircraft;
- 651 radios, and
- Personal protective clothing for the 150 fire brigades and fire fighting tools including back pack pumps for the brigades.

In 1997 fire fighting training included the following:

- 516 courses, and
- 15 480 participants trained.

Note: The equipment amounts listed were as of 1998, when the fire fighting budget was doubled from approximately $10 million to $20 million a year (Mutch *et al.* 1999). Since that time, the resource levels appear to have increased dramatically. According to Rodríguez-Trejo (1998), the federal government has 1 800 fire fighters, 133 detection towers and 145 vehicles with an additional 4 000 fire fighters, 96 observation towers and 313 vehicles being operated by owners of privately-held forests. A large percentage of the fire fighters have received advanced training.

Recent information from SEMARNAP (2000) indicates that Mexico's entire fire management programme is growing and becoming more sophisticated in response to the severe

1998 fire season. In 1999, fire prevention and suppression resources and activities increased substantially.

There are now:

- 268 fire control centres;
- 122 observation towers;
- 1 395 fire control brigades (5,845 fire fighters);
- 150 fully-equipped brigades;
- 59 detection aircraft, and
- 12 aerial bases of operation.

Goals for the year 2000 included:

- 280 operational fire control centres;
- 181 observation towers;
- 805 fire-combat brigades;
- Acquiring materials to fully equip 805 fire brigades;
- 36 helicopters for fire fighting operations, and
- 79 detection aircraft.

Mexico has also been investing in nationwide fire prevention measures including informative printed materials, training courses, extension services, formation of volunteer fire brigades, prescribed burns, and education of the populace about fire, using plays and radio and television programmes to dramatise fire prevention in pertinent social settings.

SEMARNAP also maintains sophisticated up-to-date nationwide maps of temperature, relative humidity, wind velocity, precipitation, fuel moisture, soil moisture, drought indices, fire spread rates, combustion levels, weather-based fire danger, fire intensity predictions and likely fire type (e.g. surface fire and or crowning behaviour). These data are based on numerous weather station data and a variety of models for predicting and monitoring fire conditions and behaviour been implemented with the assistance of the Canadian Forest Service. The maps can be viewed at http://fms.nofc.cfs.nrcan.gc.ca/mexico/index.html.

Nicaragua

There is a serious fire problem in Nicaragua due to a lack of human, material and financial resources. Nicaragua is currently restructuring its fire management programme (Mutch *et al*. 1999). Recently, the country started using AVHRR-derived early warning information about fires. The Nicaragua Land Resources (Fire) Monitoring Project is being carried out by the Ministerio del Ambiente los Rescursos Naturales (MARENA) and the Natural Resources Institute (NRI). A small-scale remote sensing unit is now maintained in MARENA for the benefit of forest managers and local or national decision-making bodies (Jacques de Dixmude *et al*. 2000).

Trinidad and Tobago

Trinidad and Tobago implemented the Forest Fire Protection Plan for Trinidad in 1988 in response to the severe fire season of 1987. The programme emphasises fire prevention. The annual fire management costs included $500 000 Trinidad dollars for capital expenditures on vehicles, communications, fire fighting tools and equipment. An additional $1 286 000 Trinidad dollars were spent on recurrent costs such as clearing fire traces, and patrols for fire detection and suppression (Mutch *et al*. 1999).

Uruguay

Fire fighting is aimed primarily at forest plantations. Initial responses are from plantation owners, with additional assistance provided by the Public Works Department and Defence Ministry when fires are severe. Uruguay makes use of aerial fire detection, but has no aerial fire suppression capability. An approximate fire fighting force of 1 500 personnel is maintained (Mutch *et al*. 1999).

Venezuela

Venezuela has central operation centres that support local fire response organization. A system of observation towers, aerial detection, ground patrols and trained fire fighting crews are used. Helicopters are used for transporting fire fighting personnel. More than a dozen fire fighting professionals have had international training (Mutch *et al*. 1999).