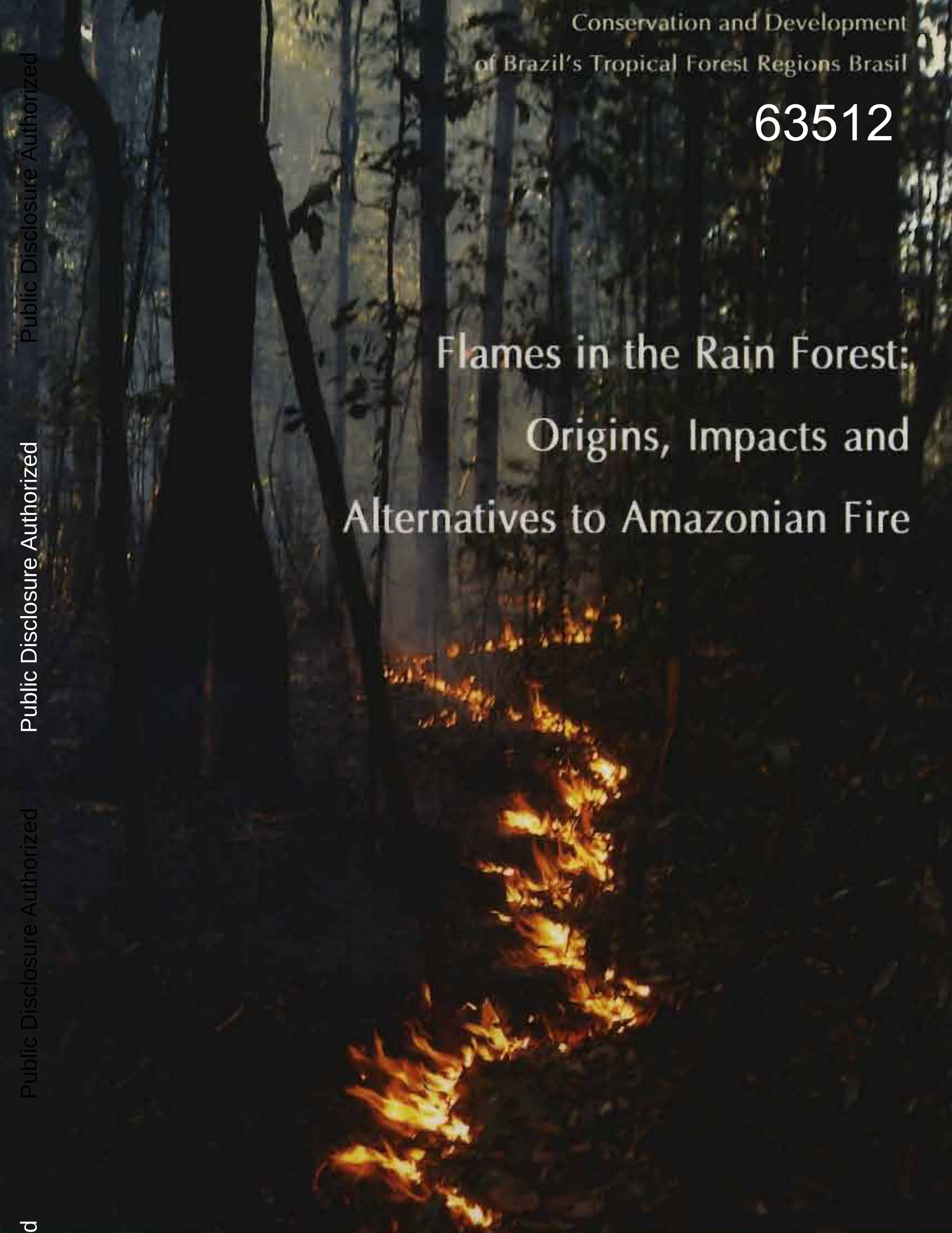

Conservation and Development of Brazil's Tropical Forest Regions Brasil

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Flames in the Rain Forest: Origins, Impacts and Alternatives to Amazonian Fire

by
Daniel C. Nepstad
Adriana G. Moreira
Ane A. Alencar

PILOT PROGRAM TO CONSERVE THE BRAZILIAN RAIN FOREST

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To F. Herbert Bormann and Otto T. Solbrig,
visionary scientists and teachers,
passionate and powerful in their application
of ecological science to public affairs.

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Executive Summary

Each year, fires in the Brazilian Amazon burn an area twice the size of Costa Rica as ranchers and farmers ignite their lands, converting forests into fields, reclaiming pastures from invading weeds, and inadvertently burning forests, grazing land and plantations in the process. The annual risk of accidental fire discourages landholders from investing in their property, and perpetuates the dominance of extensive ranching and slash and burn agriculture over fire-sensitive tree crops and forest management for timber production. Fire increases the flammability of Amazonian landscapes, initiating a vicious positive feedback cycle in which rainforests are replaced by fire-prone vegetation.

This book presents an analysis of fire in the Brazilian Amazon with the goal of identifying means by which the negative effects of Amazon fires might be reduced. Our analysis draws on several studies that have been conducted on this topic in recent years, including the first regional field study of the geographic extent and economic impact of fire, conducted in 1996.

Our analysis leads us to the following conclusions:

The flammability of Amazonian forests:

1. Most primary forests of Amazonia do not become flammable during years of average rainfall, despite the prevalence of prolonged seasonal drought in the eastern and southern portions of the region.

2. Severe droughts associated with "El Niño" episodes, and timber harvest, increase the flammability of large areas of forest; perhaps

more than 10% of the region's forests are flammable in very dry years, such as 1992 and 1998.

3. Once burned, Amazonian forests are more vulnerable to additional burning.

4. Forest fires are not a new phenomenon in Amazonia. Over the last 2000 years, severe droughts may have provoked forest burning at 400-700 year intervals. However, forest fire is much more frequent today.

Patterns of burning:

1. Amazonian fires are monitored daily by INPE using the NOAA weather satellites, which record the locations of active fires but do not provide information on what is burning, who is setting fires, and what ecological and economic effects these fires have.

2. Amazonian fires can be divided into three major types: "Deforestation fires" are associated with forest clear-cutting and burning; fires that get out of control and escape into standing primary or logged forest we call "forest surface fires"; and the burning of pastures, croplands, secondary forests and other vegetation on once-forested land we refer to as "fire on deforested land". The latter fire type can be further divided between those fires ignited intentionally for pasture and land management, and those fires that accidentally escape into cleared land.

3. We conducted a field study of 202 rural properties with a combined area of 916,257 hectares, located in five regions along the Amazon arc of deforestation. Landholders reported that a total of 77,600 hectares burned each year in 1994 and 1995, which is 8% of the study

area. When the rate of burning reported by each landholder is averaged across the properties, we find that an average of 14% of the area of these properties burned each year in 1994 and 1995, which were years of mild drought.

4. Deforestation fires burned 9,800 hectares, which is 1% of the combined property area and 13% of the entire area burned. When the rate of burning reported by landholders is averaged across the properties, deforestation fires affected 2.3% of each property and 13% of the total area that burned on each property annually.

5. A surprisingly large area of standing forest—15,500 hectares—burned each year through surface fire. This is nearly two percent of the combined property area and 20% of the total area burned. These fires affected 1.5 times more forest than deforestation burning within the study area. When the rate of burning reported by landholders is averaged across the properties, forest surface fires affected 1% of each property per year, and represented 8% of the total area burned per property.

6. Fires on land that had already been deforested burned 51,300 hectares each year, which is 6% of the combined property area and 67% of the total area burned. Landholders reported that accidental burns occurred on 36,000 hectares of deforested land each year, which is 47% of the total area burned. When the rate of burning reported by landholders is averaged across the properties, fires on deforested land affected 11% of each property per year, and represented 80% of the total area burned per property.

The ecological effects of burning:

1. Of the three types of Amazon burning, the fires associated with deforestation have the greatest ecological impacts because they lead to the rapid replacement of forest vegetation with anthropogenic ecosystems. Deforestation fires are often equated with "land use" in the tropics, and they are the focus of an intensive Brazilian monitoring program. An average of 19,000 km^2 of forests are cleared and burned each year in the Brazilian Amazon, contributing approximately 4 to 5% of the annual global flux of carbon to the atmosphere resulting from human activities. The pastures and crop fields that are planted following deforestation release less water into the atmosphere and absorb less solar energy than the forests that they replace, and may contribute to a reduction in rainfall and an increase in temperature in Amazonia.

2. Forest surface fires can kill from 10 to 80% of a forest's aboveground biomass, with large but poorly understood effects on forest fauna. Surface fires increase forest flammability and, therefore, may contribute to a vicious positive feedback cycle, in which Amazon landscapes become successively more flammable with each burning season. These fires are not included in the Brazilian deforestation monitoring program, and may double the estimated area of forest affected by human activity each year and affect larger areas during years of severe drought. Surface fires therefore release a significant amount of carbon to the atmosphere that is not included in current estimates.

3. Fires on deforested land release large amounts of smoke and particulate matter to the atmosphere, and they export nutrients from agricultural ecosystems. These fires burn an area that is twice as large as

the combined area of deforestation fires and forest surface fires, but they do not have a large effect on net carbon flux to the atmosphere.

4. Burning may result in large-scale replacement of Amazon forests by grass-dominated, fire-prone scrub. Such a "savannization" process could become self-perpetuating.

The economic costs of fires to landholders:

1. Among rural landholders in five regions, accidental pasture fires cause economic losses of approximately US$100 each year for small properties (<100 hectares) and US$15,000 each year for very large properties (>5,000 hectares). Even in years of normal rainfall, accidental pasture fires cost Amazonian landholders tens of millions of dollars.

2. These rural landholders reported annual investments in pasture firebreaks of approximately US$90 (small properties) to US$7,000 (very large properties). Firebreaks are prohibitively expensive for small-scale farmers with unproductive pastures and no access to tractors to make firebreaks.

3. Forest surface fires cause economic losses of timber, wild game, vines for construction, medicinal plants, forest fruits and other non-timber forest products that are potentially large but undocumented.

The economic costs of fires to society:

1. Fire erodes the capacity of Amazonian ecosystems to support life by releasing scarce mineral nutrients into the atmosphere, by exposing soil to the erosive force of rain and wind, by increasing surface run-

off, by destroying populations of myriad animal and plant species, and by damaging the role of forests as natural firebreaks across agricultural landscapes.

2. Fires also affect society in more direct economic ways by provoking respiratory ailments, power supply interruptions, and airport closures. In 1997, smoke closed Amazonian airports for 420 hours.

3. Fire releases globally significant amounts of carbon to the atmosphere, thereby exacerbating the global warming trend. Annual net fluxes of carbon to the atmosphere from Amazonia could double or triple during periods of severe drought and widespread forest surface fires.

Predicting fire risk:

1. An Amazonian fire risk map, RisQue98, was developed for the 1998 dry season using region-wide data on soils, rainfall, logging activity, and historical fire frequency. This map predicted that five percent of the remaining forests of the Brazilian Amazon (200,000 km^2) would have completely depleted plant-available water in the upper five meters of soil by November 1998, and were therefore highly vulnerable to forest surface fire. Another 200,000 km^2 of forest had nearly depleted their soil water by this time.

Solving the Amazon fire problem:

1. The knowledge of how to prevent and control accidental fires resides among the farmers and ranchers of rural Amazonia. They are motivated to reduce the substantial economic losses they suffer through

accidental fire. This fact is the greatest source of optimism as we analyze possible solutions to the Amazonian fire problem.

2. The losses associated with accidental fire will diminish as we develop a deeper understanding of the role of fire in rural Amazonia. Fire research in the Brazilian Amazon is virtually non-existent, and has eluded the priority-setting processes of the region's government research institutions. A program of fire research could test and improve existing techniques and social arrangements already developed by rural Amazonians to reduce fire risk and damage, as it measures the efficacy of government initiatives designed to reduce accidental fires. Field studies of the causes of forest flammability could provide the basis for a regional early warning system of forest fire risk. Economic and policy studies are urgently needed to document the costs of fire to landholders and society at large, to identify how land users can be encouraged to control and prevent fire damages, and to propose mechanisms by which the disparate public policies that influence rural Amazonia could be integrated to favor a more sustainable and less fire-prone development pathway.

3. Landholders who invest in fire prevention frequently incur the full costs of this investment, while the benefits are shared with neighbors and society in general. Farming communities can successfully achieve a more equitable distribution of the costs and benefits of investments in fire prevention and control. For example, the Del Rey community of eastern Pará has designed and implemented a community fire ordinance, which requires that: (a) community members warn their neighbors in advance of deforestation burning, (b) members circumscribe with firebreaks those areas to be burned, and (c) perpetrators of accidental fires pay their neighbors to compensate for economic losses caused by the fire.

4. The development of this capacity for local governance within farm communities is a long-term process that is accelerated by consistent inputs from dedicated, well-trained professionals, who are willing to spend much of their time working under harsh field conditions. There is a dearth of such professionals in Amazonia. Training programs are needed that provide extension agents with expertise in building the capacity of community organizations, as they teach an integrated approach to agriculture, forest management, and the wise use of fire.

5. Accidental fire presents an episodic "emergency" to Brazilian society only when severe drought and/or accelerated land-use activities greatly increase the occurrence of accidental fires during particular years, which is quite frequent (such as 1987, 1992, 1995, 1997 and 1998). Public concern about fire rises during these "emergency" years, and must be harnessed and directed into political processes that alter the long-term development model of the region. It is only in the context of a coherent, long-term approach that we can expect a gradual decrease in the use of fire by rural producers, and a gradual increase in investments to prevent accidental fire.

6. Long-term solutions to the fire problem must begin with the understanding that fire is currently a chronic, annual feature of rural Amazonia, imbedded in the culture and economic logic of farmers and ranchers. This logic is a reflection of the current development model, in which access to forests and land is high, favoring extensive land uses that rely on fire as a land management tool, and provide little incentive for preventing or controlling accidental fires. In an alternative model, forest and land could be made less accessible, which would drive up the prices of rural property and encourage the intensification of agricultural production systems, including reduced utilization of fire as a management tool, and greater investments in fire prevention

and control. There is little evidence, however, of a political constituency strong enough to effectively promote such an alternative model, nor of governmental capacity to implement this model.

7. Many current policies support the extensive Amazonian development model. Infrastructural projects bring new areas of remote forestland into the frontier and foster the type of extensive land-use practices that depend upon cheap land, and upon fire as a management tool. These projects—including the construction of roads, water ways, energy grids, and the concession of industrial mine permits—must be evaluated for their impacts on the region's demography and land-use practices. Conversely, programs that effectively protect large areas of forest located in the pathway of the expanding agricultural frontier are urgently needed.

8. Current legislative approaches are severely limited in their capacity to address the fire problem. The fire-permitting system greatly exceeds the implementation and policing capacity of environmental agencies, and is further undermined by the inability of government to assign responsibility for accidental fire.

9. Economic approaches to the fire problem could take advantage of the numerous agricultural credit and subsidy programs that exist in rural Amazonia and that currently have no requirements for fire prevention. With minor modifications, these programs could require landholders and farm communities to invest in fire prevention and control.

Preface

In early 1998, accidental fires raged out of control in parts of Brazil's northernmost state of Roraima. Under normal conditions, fires routinely set by shifting cultivators and ranchers rarely spread into the surrounding rainforests, which are too moist to burn. But a prolonged, El Niño-induced drought had dried out the forests to the point where they caught fire. The flames were finally extinguished by the rains of early April 1998 after burning about 3.3 million ha, including up to 1.3 million ha of rainforest.

The Roraima fires had critical implications for the Amazon region as a whole. Due to its location in the Northern Hemisphere, Roraima's dry season ends 4-5 months before the onset of the dry season in most of the Amazon, which lies in the Southern Hemisphere. As a result, the Roraima fires provided a wake-up call for far more extensive fires likely to occur in the rest of the Amazon—especially within the so-called "arc of deforestation" that extends along the eastern and southern edges of the region and where much of the region's rural population is concentrated. Here logging is a widespread activity and leaves large amounts of debris on the forest floor, providing fuel for wildfires. The combination of El Niño-induced droughts and increasing fuel due to logging meant that extensive areas of rainforest were under risk during the second half of 1998. This was the warning issued by the authors of this book even before the Roraima crisis began.

Prior to 1998, fire had been largely confined to areas used for agriculture or grazing. Beginning in the 1980s, researchers noted the potential risk of fire spreading to logged forests, which began to burn on a large scale in the early 1990s. But nowhere had fire posed a major threat to intact forests. The drought of 1998—building on earlier droughts in the 1990s—signaled the effective penetration of fire into forest ecosystems across much of the region and the possible initiation of a positive feedback loop in which rainforests are replaced by fire-prone vegetation.

This book is the first comprehensive analysis of fire and its new, disturbing role in the Amazon. The book builds on a 1996 study commissioned by the World Bank that examined the causes of increasing forest clearing and fires at five sites along the Amazon region's arc of deforestation. Written by a team of scientists based at the Woods Hole Research Center (WHRC) and the Instituto de Pesquisa Ambiental da Amazônia (IPAM), and with the collaboration of researchers from diverse institutions and disciplines, this book examines in detail the origins and impacts of Amazonian fires. Practiced by indigenous peoples during millennia, fire is an ancient component of the regional landscape. Until recently, its impacts were generally localized. Today, however, fire affects all major ecosystems in the Amazon and releases more than 4% of the total carbon entering the atmosphere worldwide each year.

One of the book's most disturbing findings involves the impacts of so-called forest surface fires such as those that struck Roraima. At first glance, these impacts appear to be small. Surface fires are usually confined to the forest floor, where they consume organic material and underbrush. Yet even such low-intensity fires damage the bark of rainforest trees, which slowly die during the following year. This slow death builds up substantial amounts of fuel on the forest floor, and the gradual opening up of the forest canopy reduces the high humidity in the understory, which normally protects tropical forests from burning. As a result, forests that are lightly burned by surface fires are susceptible to catastrophic fires during the following year's dry season. These findings suggest that the Roraima fires could be far worse in 1999.

In addition to analyzing the origins and impacts of Amazonian fires, the book explores alternatives that could enhance fire prevention and control. Based on a synthesis of available data on rainfall, soil and land-use practices, the authors present the first predictive model of forest fires in the Amazon. The model, which was used in preparing a World Bank emergency project for fire prevention and control in the region, provided a sobering outlook for the latter half of 1998: about 200,000 km^2 of Amazon forest were under extreme threat of burning. The data used to construct this model were admittedly deficient. For example, the Brazilian Amazon contains 60 weather stations, compared to over 1,000 in the continental United States. With improved data collection, modeling could provide a powerful tool for fire prevention and control in the Amazon.

According to the authors, the key challenge confronting policy alternatives is that many of the benefits of fire prevention and control—such as reduced emissions of greenhouse gases, protection of biodiversity, decreased flooding and erosion, and improved air quality—accrue to society as a whole, while the costs are borne entirely by individual landholders. Through enforcement of sensible policies and judicious use of economic incentives, a more balanced distribution of costs and benefits can be achieved. Finally, the authors conclude that Amazonian fires can no longer be treated only during "emergency" years, nor can they be effectively controlled by brigades of publicly financed fire fighters. Instead, fires must now be viewed as an integral part of the Amazonian landscape, and strategies for combating them must begin with the region's local communities—where creative solutions are already being tested.

The year of 1998 marked a dramatic change in the role of fire in the Amazon. Written this same year and published in early 1999, this book provides a timely contribution to public understanding and ongoing policy debate.

Anthony Anderson
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List of Acronyms

AVHRR	Advance Very High Resolution Radiometer
BASA	Banco da Amazônia
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
CESE	Coordenadoria Ecumênica de Serviços
CONAMAZ	Conselho Nacional da Amazônia Legal
CPTEC	Centro de Previsão de Tempo e Clima
CVRD	Companhia Vale do Rio Doce
ELETRONORTE	Centrais Elétricas do Norte do Brasil
EMATER	Empresa de Assistência Técnica e Extensão Rural
FINAM	Fundo de Investimento da Amazônia
FINAME	Agência Especial de Financiamento a Indústria Agrícola
FNO	Fundo Constitucional do Norte
FRD	Fundo para Desenvolvimento Regional com Recursos da Desestatização
GTA	Grupo de Trabalho Amazônico
IBAMA	Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis
IBGE	Instituto Brasileiro de Geografia e Estatística
ICMS	Imposto sobre Circulação de Mercadorias e Serviços
IIED	International Institute of Environment and Development
IMAZON	Instituto do Homem e do Meio Ambiente da Amazônia
INCRA	Instituto Nacional de Colonização e Reforma Agrária
INPA	Instituto Nacional de Pesquisas da Amazônia

INPE	Instituto Nacional de Pesquisas Espaciais
IPAM	Instituto de Pesquisa Ambiental da Amazônia
IPI	Imposto sobre Produtos Industrializados
MA	Ministério da Agricultura
NAEA	Núcleo de Altos Estudos da Amazônia
NASA	National Aeronautics and Space Administra tion (United States)
NOAA	National Oceanic and Atmospheric Adminis tration (United States)
NSF	National Science Foundation (United States)
PAGRI	Programa de Apoio à Produção Agrícola em Comunidades da Amazônia
PAI	Programa Amazônia Integrada
PPG7	Programa Piloto para Conservação das Florestas Tropicais do Brasil
PROCERA	Programa de Apoio à Reforma Agrária
PRONAF	Programa Nacional de Fortalecimento da Agricultura Familiar
PSU	Pennsylvania State University
SUDAM	Superintendência de Desenvolvimento da Amazônia
UC	University of Colorado
UFAC	Universidade Federal do Acre
UFPa	Universidade Federal do Pará
UnB	Universidade de Brasília
USAID	United States Agency for International Development
UW	University of Washington
WHRC	Woods Hole Research Center

List of Collaborators

This book was shaped by the ideas, conversations and critical comments generously shared with us by the following friends and colleagues:

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and

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1. The Problem of Amazonian Fire

Amazon fires close airports, send thousands of people to health clinics with asthma and bronchitis, and provoke traffic collisions. Rampaging brush fires kill livestock, burn fences, and destroy crops, orchards and plantations. But these fire-related headlines miss the full magnitude of the Amazon fire problem. Fire is the single greatest threat to the biological integrity of the largest, richest tropical forest on the planet. The risk is that this exuberant forest will be transformed into an impoverished patchwork of weedy, pyrogenic vegetation through the synergistic effects of increasingly severe droughts and human activities that erode the forest's resistance to fire. The purpose of this book is to review and synthesize the state of our knowledge of the problem of Amazonian fire, and to apply this knowledge to an analysis of potential solutions to this problem.

The enormous importance of fire in Amazonia can be explained by its paradoxical status as both an essential tool for converting forests to crop- and rangeland, and as an agent of destruction when it burns beyond the desired boundaries, destroying forage, tree crops and fencing, and impoverishing forests. Fire is the necessary evil on the agricultural frontier of Amazonia, enhancing the short-term productivity of farms and ranches, but discouraging investments in fire-sensitive perennial crops, forage, and fencing, and reducing the economic viability of forest management for timber production. As long as the people of rural Amazonia continue to depend upon fire to push back the agricultural frontier and maintain their agricultural systems, the residual forests of agricultural landscapes will be impoverished as surface fires kill trees and lianas, deplete populations of animals, and render the forests more susceptible to future burns.

The problem of Amazonian fire begins with the immense usefulness of fire in forest conversion to agriculture and weed control. It is so useful that it is virtually an inseparable feature of the agricultural frontier. Burning is the cheapest method for converting the nutrients contained in cut and dried forest trees into soil-fertilizing ash, disposing of the tangle of felled trees and branches in the process. Without fire, landholders must invest in heavy machinery to clear their land of felled trees, thereby foregoing the short-term improvements in soil fertility that arise from the input of ash. Without fire, landholders must invest more money to control woody weeds in their cattle pastures by mowing or by cutting the weeds with machetes. Fire is the cheapest way of pushing the agricultural frontier into the forest, and it is the cheapest way of preventing the forest from reclaiming grazing lands through natural regrowth.

Fires become a problem especially when the burns set to convert forests to crop- or rangeland, or to control weeds, escape their intended boundaries, which is a frequent occurrence on the Amazon frontier. Several factors contribute to the likelihood that intentional fires will escape and cause large ecological and economic damage. First, fires are usually set toward the end of severe dry seasons, when forests and croplands are most vulnerable to fire. Four fifths of the deforestation that has taken place in Brazilian Amazonia to-date occurred where the dry season is long and severe (Fig. 1.1). Settlers have occupied the seasonally dry eastern and southern flank of Amazonia because it is accessible by roads, because it is closest to the regions they are emigrating from in northeastern and southern Brazil, and because the soils in this region are generally more fertile than the soils of the relatively wet central and northeastern portions of Amazonia (Richter and Babaar 1991, Cochrane and Sanchez 1982). Landholders set their intentional fires late in the dry season to achieve good burns with high degrees of

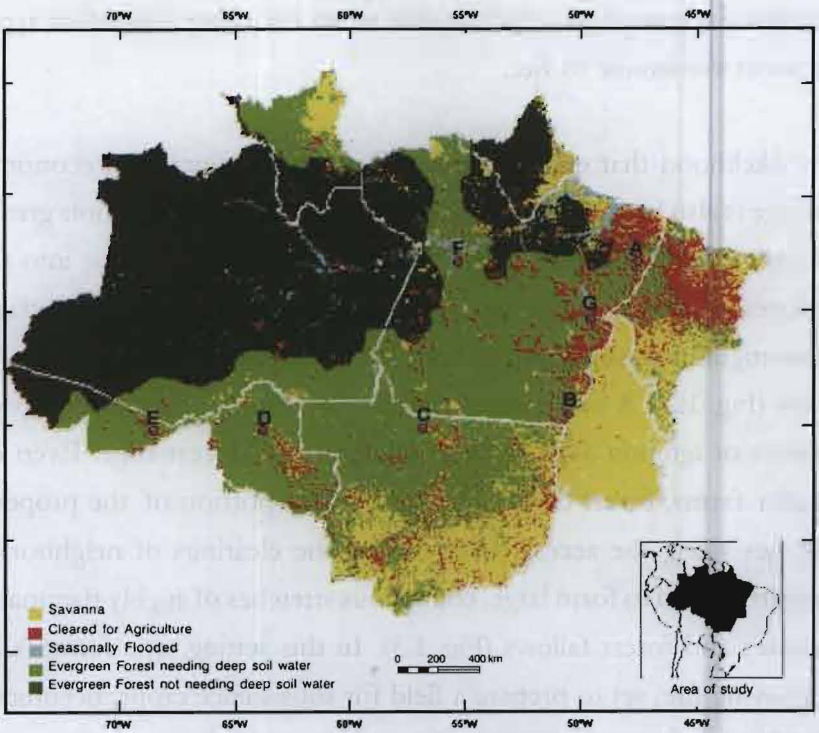

Figure 1.1 This map of the Brazilian Amazon shows how the area of closed-canopy forest that has already been deforested (red) is concentrated in the seasonally-dry portions of the region, where average daily rainfall during the dry season is less than 1.5 mm per day (isobars, and areas of light green forest). The study sites that are referred to in this book (A through G) are spread throughout this "arc of deforestation", and include: A. Paragominas, Pará, B. Santana do Araguaia, Pará, C. Alta Floresta, Mato Grosso, D. Ariquemes, Rondônia, E. Rio Branco, Acre, F. Santarem (Belterra), Pará, G. Marabá, Pará. Savannas and deciduous forests (yellow, 14%) were separated from evergreen forests (75%) based on seasonal patterns of canopy greenness as seen from satellite imagery and a vegetation map (Stone et al. 1994).

biomass consumption, which is also when the other vegetation types are most vulnerable to fire.

The likelihood that escaped fires will cause ecological and economic damage is also high because the dominant land uses in Amazonia greatly increase the flammability of the landscape. Fires that escape into the pastures of large ranches may burn hundreds or thousands of hectares of contiguous pastureland without having to jump across streams or roads (Fig. 1.2). A single accidental pasture fire can therefore provide sources of ignition along tens of kilometers of forest edge. Even on smaller farms, forest clearing begins on that portion of the property that lies along the access road, so that the clearings of neighboring properties tend to form large, contiguous stretches of highly flammable pastures and forest fallows (Fig. 1.3). In this setting, one farmer's labor-saving fire, set to prepare a field for subsistence crops, becomes a neighboring farmer's nightmare as fencing and forage supply are destroyed by an escaped blaze.

Fortunately, the matrix of tall, dense forest into which agricultural clearings are cut extends like a giant firebreak across the landscape, preventing the spread of most escaped agricultural fires. Even at the peak of the dry season, these deeply-rooting, drought-resistant forests resist burning because their dark shady interiors maintain the moisture in the dead leaves and twigs on the forest floor, preventing them from catching fire (Holdsworth and Uhl 1997, Nepstad et al. 1994, 1995; Uhl et al. 1988a; Uhl and Kauffman 1990). But the fire-break function of these forests is damaged when logging operations cut gaps in the forest canopy, allowing sunlight to reach the forest floor, drying out the leaves and twigs that are necessary to carry a fire. And when droughts are particularly severe, even unlogged forests are rendered flammable

Figure 1.2 The landscape around Paragominas, Pará, in eastern Amazonia, as seen from satellite. As in many Amazonian landscapes, a single fire that escapes from a pasture (blue and orange) can set hundreds of hectares of forest on fire. Few natural barriers to the spread of fire remain in this mosaic of large pastures and selectively logged forests. In this image, more than half of the forests have already been burned (light green, outlined in black). This image was made using color composite bands 4, 5 and 7 of a Landsat Thematic Mapper satellite image taken in June 1993.

Figure 1.3 Satellite image of Ariquemes, Rondônia, where 100-hectare, rectangular lots are laid out along roads. Since farmer colonists begin clearing their land along the roads, large areas of contiguous crop- and pasture-land are created that can conduct escaped fires across several properties. Landsat TM image, taken in 1995. Forests appear dark green, while cleared areas with secondary vegetation are light green, and areas of bare soil and urban areas appear pink and purple.

by the leaf shedding that is triggered when trees run out of soil water (Nepstad et al. 1995, 1998).

The likelihood that intentional agricultural fires will escape into neighboring properties or ecosystems is exacerbated by market and policy failures. In today's rural Amazonia, it is often simply not worth the investment required to prevent agricultural fires from escaping. Firebreaks can be made around fields that are to be burned to contain fires, or they can be made around pastures, croplands or forests that need to be protected from fire, by clearing the vegetation from strips of land using machetes or bulldozers. But this considerable annual investment in fire prevention only makes economic sense if the benefits derived through the protection of crops, forage, fencing, or timber are greater than the cost of the firebreak, or if the land-user faces certain and significant penalties for damaging neighboring property or for wider environmental impacts. And these benefits can be very low, particularly in the early stages of frontier development, when land (and forest) is abundant, and productivity is low. If the timber has already been harvested from a forest, or if a pasture is overgrazed and unproductive, or if a farm's production is based primarily on subsistence crop production through slash and burn agriculture, then the direct economic damages to landholders associated with escaped fires may be quite low, even if the damages to society of forest burning are very high. From the perspective of the private landholder, investments in fire prevention make more sense as investments are added to the land such as fencing, tree crops, timber management, and fire-sensitive forage grasses. Likewise, fire prevention and control makes more sense when penalties for external damages are more likely to be enforced, which is not the case in Amazonia.

The problem of Amazonian fires is particularly difficult to resolve because it is the outcome of a complex interaction of biophysical and socio-economic factors operating on the Amazon frontier. Fire is deeply imbedded in the culture of rural Amazonia. Burning is the most efficient way for a farmer or rancher to push back the forest (and keep it back), but fire is particularly difficult to contain within prescribed boundaries in the seasonally-dry regions of Amazonia where most people are settling, and where virtually every land-use activity increases the land's flammability. Fire is difficult for the central government to regulate because it happens quickly, in remote regions, and it is often impossible to prove how a fire started, to determine the amount of economic damage that a fire caused, and to assign and enforce liability for those damages.

But solutions to the fire problem may be within the reach of Brazilian society. Educational campaigns could encourage landholders to employ conventional fire prevention and suppression techniques more diligently. Implementation of existing fire legislation enacted at the level of central government, by state or municipal governments, or by local forms of government established among communities of farmers, could reduce the occurrence of accidental fire. Economic tools involving taxes and credit programs hold strong potential for increasing landholder incentives to invest in fire prevention techniques, and in social arrangements that reduce fire risk. In the long term, however, no approach to the burning problem in Amazonia will succeed without fundamental changes in the way that the region is being developed. Fire is an inevitable feature of new frontiers where land and forests are cheap, and extensive approaches to agriculture and forestry are the most profitable. A model of Amazonian development is needed that restricts access to large areas of forest, while increasing the profitability of agricultural and forestry production in landscapes that are already occupied. Under these conditions, production systems should intensify. It is in the context of greater agricultural and forestry productivity within a contained Amazonian frontier that fire will become less attractive as a management tool, and that investments in fire prevention will make economic sense to Amazonia's rural producers.

2. Forest Flammability

2.1 The three ingredients of a forest fire

At any latitude, in any ecosystem, the three requirements for a fire are fuel, dry climatic conditions, and a source of ignition. The most flammable ecosystems have an abundance of fine, easily-ignited fuel that is close to the ground and very dry. At the top of the list of highly-flammable ecosystems are the grasslands and savannas of the world that are subjected to severe seasonal drought. Whether in Africa, central South America, or central North America, the world's seasonally dry grasslands and savannas burn easily because grasses provide an abundant, well-aerated supply of fine fuel close to the ground. Seasonal drought and direct solar radiation allow this fuel layer to dry so that it is easily ignited.

Forest ecosystems are generally more difficult to ignite than grasslands and savannas, even though they contain more fuel. This is because the fuel in forests is higher off the ground than in savannas, and much of this fuel is in woody stems that require longer fire contact times to ignite than dry leaves. Fires in closed-canopy forests can therefore be divided into two broad categories: surface fires and crown fires. In the former, the fire consumes the layer of fine fuel (dry leaves and twigs) on the forest floor. In the latter, the fire moves into tree crowns, potentially consuming most of the forest's aboveground biomass.

Forests are also more difficult to ignite than grasslands and savannas because of the shady moist microclimate of the forest interior. As much as 98% of the sunlight that shines on a moist tropical forest canopy, for example, never reaches the fine fuel layer on the forest floor (Chazdon et. al. 1996, Fetcher et al. 1985, Nepstad et al. 1996b) but, rather, is absorbed or reflected by the canopy. If the air is humid, as is usually true in moist tropical forest regions, then the fine litter layer will only lose its moisture and become flammable if the air temperature rises during the day, lowering the air's relative humidity. As we shall see in the subsequent section, it is this interaction between the shade cast by the forest canopy and the moisture content of the fine fuel layer that is the critical determinant of forest flammability in Amazonia.

2.2 Rainforests in a desert: the paradox of evergreen forests in eastern and southern Amazonia

The forests of Paragominas

To walk through a virgin forest near Paragominas in November is to confront an ecological paradox. Only an inch (25 mm) of rain has fallen over the last 3 months, and yet the foliage is still lush and dense. Because of the shade cast by the vaulted green ceiling above, the air is damp inside of the forest, and the ankle-deep layer of dead leaves and twigs on the ground makes a muted swooshing noise—not the papery rustle of dry leaf litter. Even at the peak of the annual drought, the forest is soaking up carbon dioxide from the air through the process of photosynthesis, and releasing 3 or 4 mm of water to the atmosphere each day. The paradox, then, is encountered when we try to interpret the forest's remarkable tolerance of drought from the conventional view of tropical rainforests. If it is as shallow-rooted as the textbooks would have us believe (Jordan 1985, Richards 1952), then this forest should have run out of water stored in the upper meter of soil several weeks ago. It should have shed its leaves and, in the process, built up a thick layer of leaves on the ground that are desiccated by the sunlight streaming through the naked treetops. After a drought of this severity, this forest should be a tinderbox!

To understand the forest's remarkable tolerance to drought—and its resistance to fire—we must abandon the notion that tropical forests are shallow-rooted. The roots of this Paragominas forest extend down into the soil to at least 18 meters depth (Nepstad et al. 1994). The deep clay soil upon which the forest grows acts as a very large sponge which is dried out by the forest during the dry season as the deep root system absorbs soil water. This sponge is then replenished with water during the rainy season (Fig. 2.1). During most dry seasons, this "buffering" capacity of the sponge is sufficient to supply the forest's water needs, and the forest does not shed enough leaves to become vulnerable to fire. Uhl and Kauffman (1990) measured the flammability of the Paragominas forest during an "average" year (1988)—a year without El Niño-related drought—and elegantly documented the daily cycle of fine fuel moisture content during the course of the day and during the course of a 16-day period without rain (Fig. 2.2). Fine fuel moisture content accompanied the daily march of the air's dryness, which climbed and descended as the forest interior heated up and cooled down. During the 16-day measurement period, the fuel never dried sufficiently to be ignited.

But during very severe dry seasons, the forest can suck the soil dry to depths of more than 5 meters, provoking drought stress in the trees, triggering leaf shedding, and increasing forest susceptibility to fire. For example, during the severe El Niño episode of 1992, the

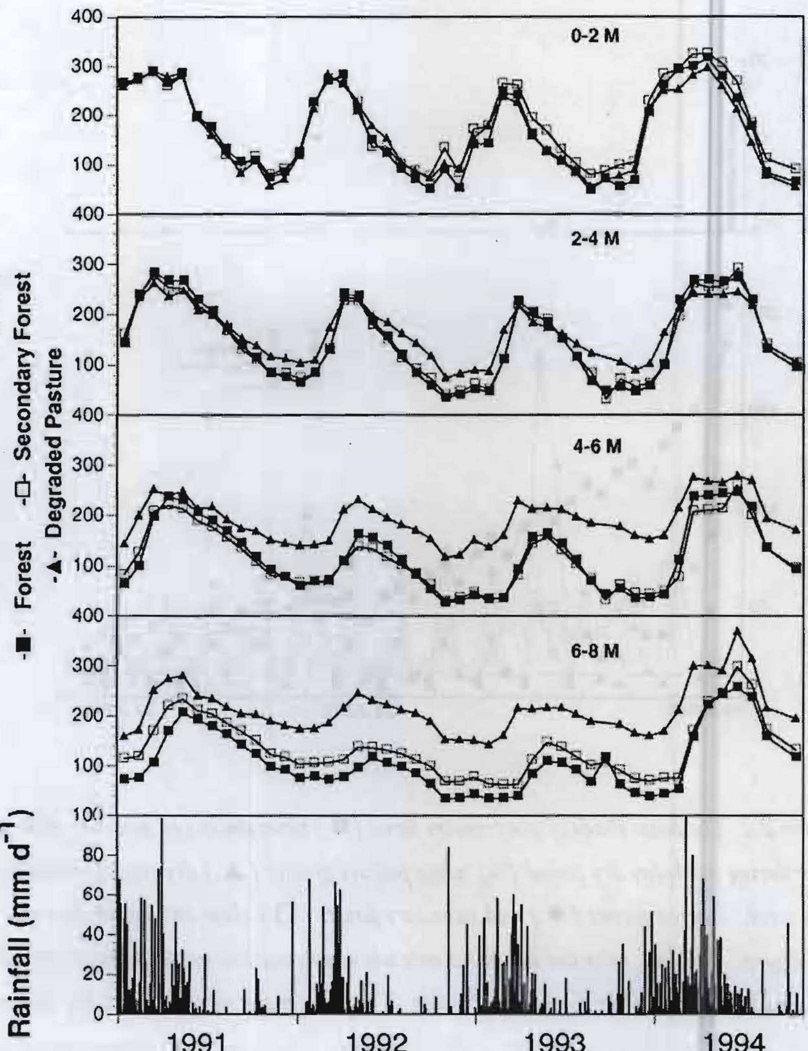

Figure 2.1 Four-year record of the amount of soil water that is available to plants to 8 meters depth in two-meter intervals, for undisturbed forest (■), 15-year old secondary forest on abandoned pasture (▲), and degraded pasture (□) at the Fazenda Vitória study site, Paragominas, PA. Daily rainfall is displayed in the lowermost panel. This graph illustrates how the 1991 depletion of soil water below 4 m depth in the forest and secondary forest persisted until the 1994 rainy season, because of below-average rainfall in 1992 and 1993. This inter-annual drought brought the mature forest very close to the flammability threshold, at which point soil moisture depletion triggers leaf shedding, increasing the flammability of the forest floor. Adapted from Jipp et al. 1998.

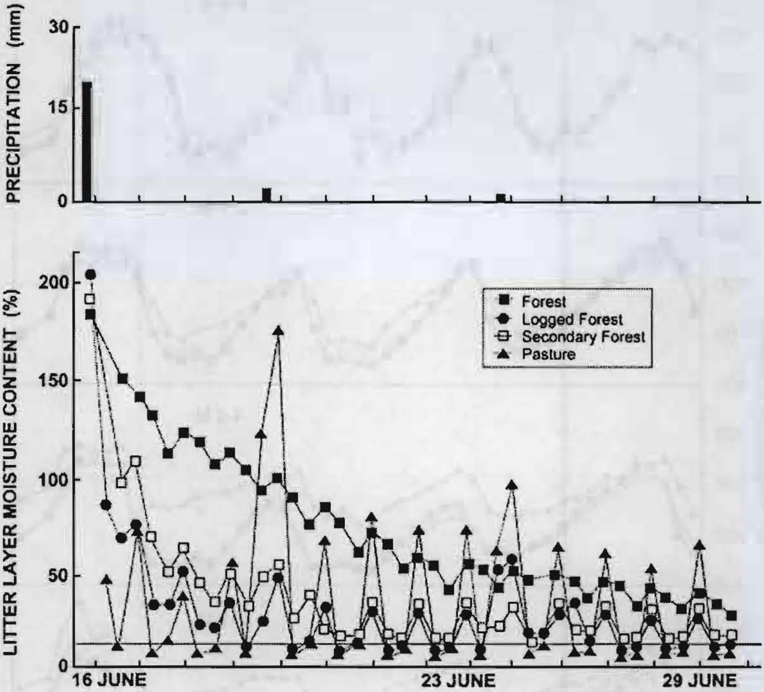

Figure 2.2 The dense shade of the primary forest (■) slows the loss of moisture from leaf litter during a 14-day dry period (%), while pasture grasses (▲) dry rapidly following a rain event. Logged forests (●) and secondary forests (□) show an intermediate rate of fuel drying. The leaf litter can be ignited only when moisture content drops below approximately 15%, indicated by the horizontal line. The pasture can therefore catch fire within a day of rain, while the forest requires weeks of drying. The logged forest requires one to two weeks of drying to become flammable. From the Vitoria Ranch, near Paragominas, Pará, Brazil. Source: Uhl and Kauffman 1990.

Paragominas forest depleted the water in the upper 8 meters of soil (Fig. 2.1). Toward the end of this study, some of the tree species that were being analyzed showed precipitous increases in drought stress as the water uptake lagged behind water loss through their leaves (Fig. 2.3). The leaf area during this severe dry season declined to 85% of the rainy season maximum (Fig 2.3). By the end of the 1992 dry season, the Paragominas forest crossed the threshold of flammability.

The Paragominas forest's dependence upon water stored deep in the soil has a very important side effect: once this deep-soil "sponge" is dried during a severe dry period, it may require years to be replenished. Put another way, a severe drought can persist in the soil for years—completely invisible when observing the forest above the ground—rendering the forest more vulnerable to further drought. After the drought of 1992, the soil beneath the Paragominas forest remained depleted of moisture below 4 meters depth until midway through 1994, when the rains were finally sufficient to recharge the soil all the way to 8 meters depth (Fig. 2.1). But until this recharge finally occurred, the forest was precariously vulnerable to another year of low rainfall, because the soil had insufficient moisture to buffer the forest from severe drought.

By October 1997, the forest of Paragominas was pushed over the threshold of flammability as a record-breaking drought exceeded the capacity of the soil to buffer the forest against the effects of rainfall shortage. For the first time in 13 years of observation, the Paragominas forest was flammable. During a 200-day period beginning on May 6, a total of 88 mm of rain fell on the Paragominas forest. During this same period, approximately 800 mm of water were removed from the soil by the forest and lost to the atmosphere through evapotranspiration. Moreover, during the 80-day period beginning on August 12, there

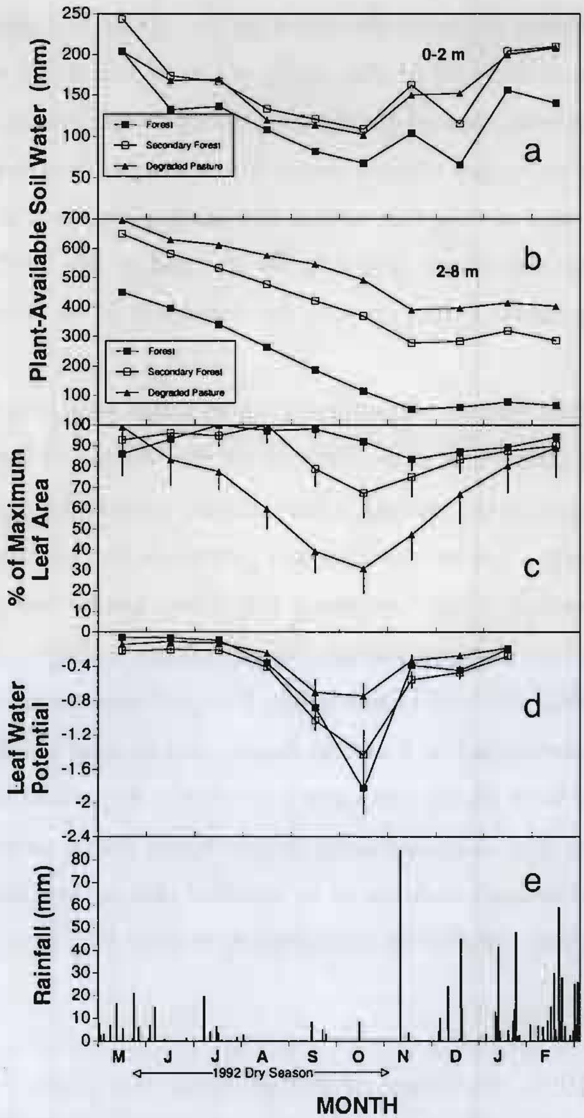

Figure 2.3 Primary forests can catch fire if severe drought provokes leaf-shedding, and the subsequent drying of the leaf litter layer. During the severe dry season (e) of the 1992 El Niño event, in Paragominas, Pará State, the virtual depletion of plant-available soil moisture to a depth of 8 meters (a and b) was needed to trigger leaf shedding (c); secondary forest and cattle pasture began to reduce their leaf canopies much earlier in the dry season (c). The forest was rapidly developing severe drought stress, however, as indicated by the plummeting leaf water potential (d), and may have been on the verge of much more extensive leaf shedding. Adapted from Nepstad et al. 1994, 1995.

was not a single rain event in Paragominas. Even prior to the peak of the dry season, the experimental fires that we started on the forest floor with the help of kerosene, quickly spread and had to be extinguished. The leaf area of the forest, which had declined to 85% of its maximum value during the 1992 El Niño event (Fig. 2.3), dropped to 75% of its maximum value in 1997. The green leafy canopy of the forest was quickly being shed as tremendous tensions developed in the internal water columns of the trees and lianas, which could not absorb soil moisture quickly enough to replace the water lost through evapotranspiration.

Amazonian forests at the drought threshold

As this book goes to press, the Paragominas forest—and large expanses of primary forest in eastern and southern Amazonia that were also subjected to severe drought—are precariously vulnerable to another severe dry season. In many regions of Amazonia, the rains in 1998 have been sufficient to extinguish the fires of the 1997 burning season, but they have been inadequate to recharge the moisture that was extracted from the soil during the 1997 dry season. Hence, the ability of the deep soil "sponge" to buffer these forests against the effects of drought on leaf shedding and fire susceptibility is reduced, as it was in the Paragominas forest in 1993 (Fig 2.1)

The current water deficit in eastern and southern Amazonia is dramatically illustrated through a comparison of the cumulative amount of rainfall that has fallen since July 1997 with the average amount of rainfall that falls in other years (Fig. 2.4). As of April 1998, rainfall in locations more than 1000 km apart was 500 to 1200 mm below average.

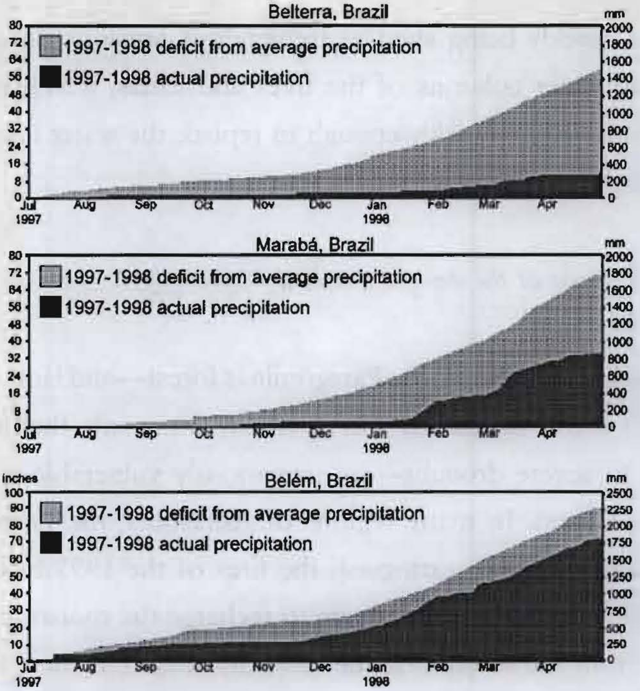

Figure 2.4 El Niño events are usually associated with rainfall reductions in much of the Amazon region. During the 1997-98 El Niño event, cumulative rainfall (dark area along the bottom) lagged far below the average cumulative rainfall (dark area plus gray area) in the widely separated cities of Belterra, Belém, and Marabá. In Belterra, rainfall was 1000 mm below average for the nine month period beginning July 1997! Regions shaded in gray show precipitation deficits. Source: Climate Prediction Center/NOAA.

The fires of the northern Amazonian state of Roraima, which captured the world's attention in February and March of 1998, may be a harbinger of a much larger forest fire problem in Amazonia, in which severe seasonal drought exceeds the capacity of deep Amazonian soils to buffer forests against the leaf-shedding that increases their vulnerability to fire. This topic is explored in greater depth in Chapter 4, in which we describe a model for predicting fire risk in Amazonia, and present a map of those forest areas which became vulnerable to fire in the 1998 dry season.

Pre-Columbian forest fires

Several lines of evidence suggest that severe droughts have provoked Amazonian fires in millennia past, and that these droughts were the result of severe El Niño episodes. Charcoal found in the soil of rainforest in San Carlos de Rio Negro, in southern Venezuela, has been dated at ~250, 400, 650, 1500, 3000 and 6000 years before present, and it is unlikely that this charcoal was produced by human activities (Saldarriaga et al. 1988, Sanford et al. 1985). These dates correspond to dry periods as documented through pollen studies in the region (Sanford et al. 1985). Under the current rainfall pattern of this region, which is characterized by a very mild annual dry season, the closed-canopy rainforests do not dry sufficiently to be ignited (Uhl et al. 1988a). Similarly, evidence of ancient fire events that corresponded with severe drought over the last 7000 years has been drawn from pollen and radiocarbon dating studies conducted on sediments of Carajás lake sediments, in eastern Amazonia (Turcq et al. 1998).

Meggers (1994) has found that the ages of the San Carlos charcoal correspond to discontinuities in the ceramic patterns of indigenous Amazonian populations, and to flooding along the Peruvian coast (where El Niño Southern Oscillation leads to greater rainfall). She advances the hypothesis that very severe "Mega-Niño" events occurred at approximately 400, 700, 1000 and 1500 b.p, and that these events led to droughts in Amazonia that were severe enough to cause widespread fire, water shortages, and the dispersal of indigenous populations. She argues that these periodic disruptions of pre-Columbian Amazonian societies triggered the diversification of both ceramic patterns and languages. This evidence of catastrophic fires in recent centuries provides a warning for the people of today's Amazonia. Fire has the potential to profoundly disrupt human society in the region.

2.3 Logging effects on flammability

The Amazonian wood industry has grown rapidly in response to improved extraction methods and increased access to domestic and international markets for sawn wood, veneer, and plywood (Stone 1997). The depletion of forests in southern Brazil and the dwindling stocks of timber in tropical forests around the world have made Amazonia the largest remaining source of tropical timber in the world (Uhl et al. 1997).

Although the methods used to extract wood from Amazon forests are "selective"—that is, only a small number of trees are harvested from a given forest—they greatly increase the susceptibility of forests to fire. In the most common form of wood extraction, a crew of woodsmen mark mature individuals of desirable (marketable) tree species, and is followed by a chain saw crew that cuts down the marked trees. Bulldozers drag the felled trees out of the forest into a *patio*, or log yard, which has been cleared in the forest. This log yard is big enough

Figure 2.5 A recently logged forest on the Vitoria Ranch, near Paragominas, Pará State, which burned one month after this photograph was taken. Logging crews perforate the canopy of forests by opening clearings where logs are loaded onto trucks, by felling trees, and by dragging tree boles into the clearings. Large amounts of fuel are left on the forest floor, which is dried by the sunlight that comes streaming through the perforated canopy. (Photograph by D. Nepstad)

for trucks to be loaded with logs and is connected via rustic road networks to the state or federal feeder highways (Fig. 2.5). The watchword in these logging operations is "speed", as sawmills strive to secure enough timber to carry the mill through the rainy season, when the slippery clay soils prevent logging trucks from entering the forests. Since the forest is either not owned by the sawmill that is exploiting it, or the prospect of a second or third harvest from the forest is small, there is little concern for wastage during the harvest operation (Johns et al 1996). The trees that are cut are frequently bound to neighboring trees by vines and they are felled with little regard for potential damage to these neighbors; hence, up to 20 trees can be knocked down or damaged for every individual that is harvested (Uhl and Vieira 1989). The trees selected for harvest are rarely mapped, and bulldozers cause more damage than is necessary as they wander through the forest in search of felled trees.

The rapid, careless methods that are employed to harvest wood from Amazonian forests can significantly increase their flammability. The most extreme forms of selective logging reduce forest canopy cover from 95% down to 50%, and remove, kill or damage up to 40% of all adult trees (Fig. 2.5). The amount of woody fuel increased from 51 tons per hectare in a mature forest to 180 tons per hectare after logging at the Fazenda Vitoria experimental forest in Paragominas (Table 2.1). Moreover, because of the drastic reduction in leaf canopy cover, mid-day vapor pressure deficit (a measure of the evaporative capacity of the air) was four times higher in the treefall openings of the logged forest than in the shaded interior of the primary forest, and maximum air temperatures were 10 degrees C higher in the logged forest (Table 2.2). Leaf litter dried out much more rapidly than in the primary forest, and fell below the moisture content of the fuel ignition threshold (approximately 15%, Uhl and Kauffman 1990) within 5 or 6 days of a rain event. In contrast, moisture content of the leaf litter in the primary forest was above the fuel ignition threshold even after 14 days without rain (Fig. 2.2).

The effects of selective logging on forest flammability can be reduced through careful wood harvest techniques that damage or kill fewer trees than the traditional "high impact" harvest techniques (Holdsworth and Uhl 1997). By mapping out the trees to be harvested, cutting vines that connect the selected tree to its neighbors, planning the direction of the tree fall, and removing the felled tree boles with a rubber-tired skidder, these "low impact" harvest techniques can reduce the mean size of treefall gaps by 53% (Johns et al. 1996) and leave canopies more closed than conventional logging practices. Gap size is an important determinant of flammability, because the rate of fuel drying is dependent upon the amount of direct sunlight that reaches the fuel, and large gaps receive much more sunlight than small gaps (Holdsworth

Table 2.1 Mass (Mg/ha) of litter and woody fuels in selected plant communities at Vitoria Ranch near Paragominas, Pará, Brazil. Data are means +/- SE.* Source: Uhl and Kauffman 1990.

Fuel class	Primary forest	Logged forest	Pasture	Second-growth forest
Litter (fine fuel)	4.1±0.2[a]	6.1±0.3[b]	11.3±1.6[c]	4.2±0.0[a]
Total wood fuels	51.5±16.2[a]	172.7±41.2[b]	40.2±22.0[a]	23.4±6.7[a]
Total (combined litter and woody fuels)	55.6±16.2[b]	178.8±41.2[a]	51.5±22.1[b]	27.7±6.7[b]

* Different superscripted letters denote a significant difference between plant communities at $p<0.05$

Source: Uhl & Kauffman 1990

Table 2.2. Midday (13:00 h) relative humidity (RH) and vapor pressure deficit (VPD), and the average diurnal temperature maxima (T_{max}) and temperature minima (T_{min}) over 62 consecutive days in four vegetation cover types at Vitoria Ranch near Paragominas, Pará, Brazil. Data are means ± SE. Source: Uhl and Kauffman 1990.

Microclimate Variable	Primary forest	Logged forest	Pasture	Second-growth forest
Midday RH (%)	85.6±0.7	65.3±1.0	50.6±1.4	61.6±1.1
Midday VPD (kPa)	0.53±0.3	2.30±0.07	3.44±0.06	1.99±0.07
Diurnal T_{max} (°C)	27.7±0.2	37.5±0.3	38.2±0.2	32.9±0.5
Diurnal T_{min} (°C)	22.0±0.1	21.8±	19.9±0.2	20.8±0.1

and Uhl 1997). These low-impact harvest techniques are rarely employed in Amazonia, perhaps because they are more expensive than traditional techniques, costing an additional $72/ha more than conventional harvest techniques (Barreto et al. 1998), or because there are few firms that harvest timber with the intent of returning to the same forest for a second harvest decades later because of the sheer abundance of primary forest.

Like low-impact harvest techniques, those forms of harvest that remove only small amounts of wood from the forest also have a small effect on forest flammability. The most extreme example of low-intensity wood harvest is mahogany, in which an average of only 5 m³ of wood are removed per hectare vs. 30-40 m^3 per hectare in intensive forms of harvest (Veríssimo et al. 1995). Since mahogany trees are clumped together, the effects of harvest on forest flammability are very localized, and most of the forest is unaltered in its vulnerability to fire.

2.4 Burning leads to burning

Like logging, forest surface fires increase forest flammability by allowing more sunlight to reach the forest interior and by increasing the amount of woody fuel. Most of the fires that enter standing Amazonian forests—whether logged, drought-stressed or both—move slowly along the forest floor, burning leaf litter with flame heights of 40 cm or less (Fig. 2.6), and occasionally climb into the canopy where trellises of fuel permit. Patches of forest often escape burning because of barriers to fire transmission along the ground, lack of fuel, or locally high fuel moisture associated with dense shade (Holdsworth and Uhl 1997, Fig. 2.7). At first glance, surface fires appear to be rather innocuous, with little impact on the structure of the forest. However, surface fires kill many of the trees and lianas that they contact, especially those species that have thin bark or that are in other ways sensitive to fire (Uhl and Kauffman 1990).

Within days of a surface fire, the forest begins to shed its leaves, blanketing the forest floor with a new layer of fuel and greatly increasing the amount of sunlight that reaches this fuel. Many trees shed their leaves because their stems are killed by the fire. But many trees that are not killed by the fire shed their leaves as well, perhaps because of the direct influence of crown scorch and smoke exposure.

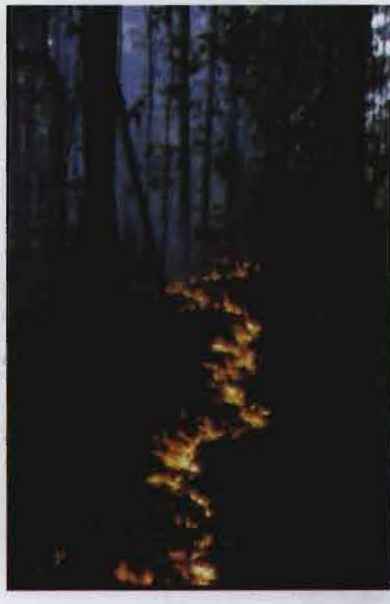

Figure 2.6 Forest surface fire burning the litter layer in the interior of a logged forest near Tailândia, Pará, Brazil. Fuel moisture contents are high in the forest interior, and flame heights therefore remain low. Crown fires are currently a rare occurrence in Amazonian forests. (Photograph by M. Cochrane)

Shortly after a surface fire, some forests contain sufficient dry fuel to burn again, and smoldering tree stems can provide a source of new ignition (M. Cochrane and M Schulze, in press).

In subsequent years, the burned forest is highly flammable as trees and lianas killed by the fire lose their branches or fall to the ground, punching new holes in the forest canopy and building up the woody fuel layer. Cochrane and Schulze (in press) have documented the dramatic increase in forest flammability that accompanies each successive burn in logged forests of central Pará (near Tailândia). Whereas a forest that has never burned requires weeks without rainfall to become flammable, approximately half of the area of a forest that has experienced a surface fire becomes flammable within 9 to 16 days of the last rain event. With further burning, virtually all of the forest area can be ignited after 9 days without rain (Fig. 2.8). One of the most important effects of large-scale forest fire is the increased susceptibility of these forests to further burning (Section 3.7).

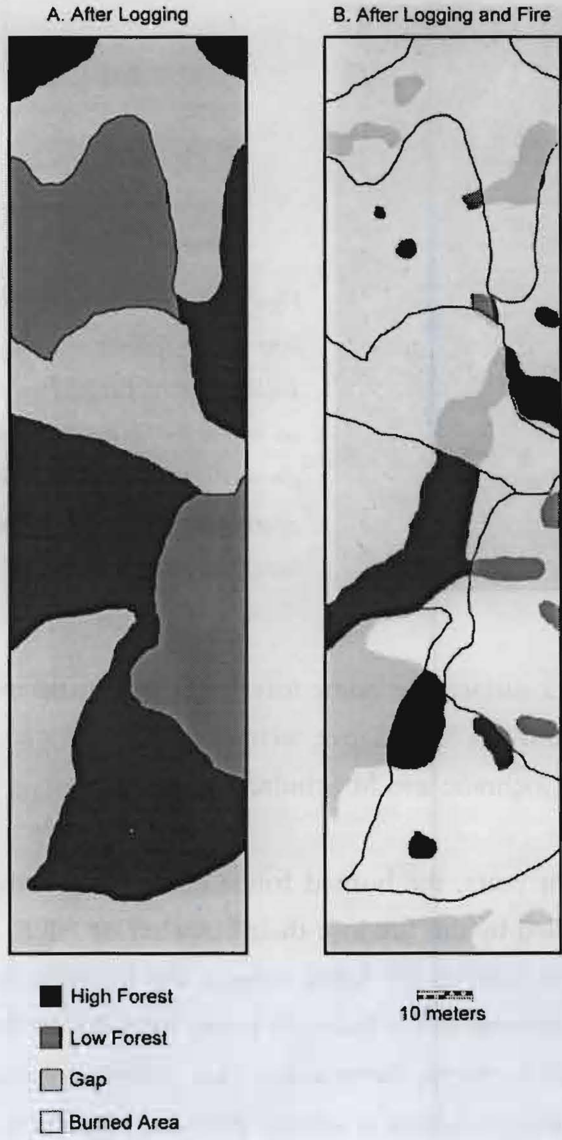

Figure 2.7 Forest surface fires burn the forest floor incompletely, leaving islands of unburned forest, particularly where the forest canopy is high and dense. In this "before and after" drawing of a 50 x 200 m section of a logged forest that burned in 1992, cover classes include high-forest (15-30 m), low forest (6-15 m, heavily covered with vines), gap (areas where trees were extracted), and burned areas (areas where fire burned the litter layer). Source: Holdsworth and Uhl 1997.

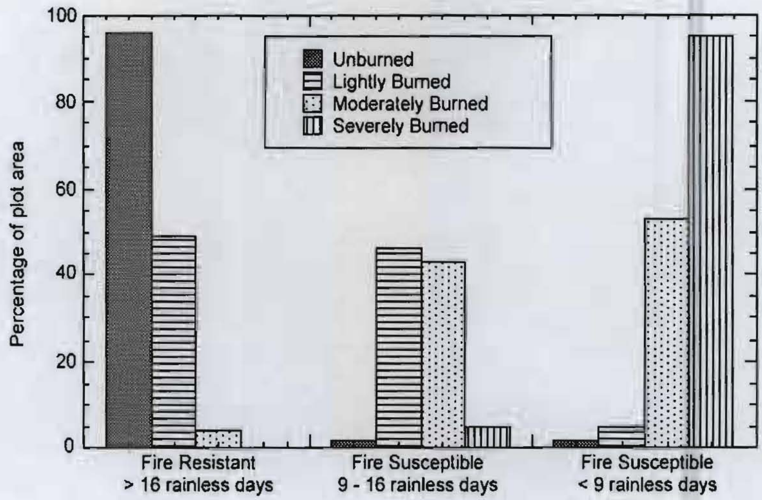

Figure 2.8 With each successive surface burn, forest canopies become more open, allowing greater amounts of sunlight to penetrate down to the forest floor, speeding the rate of drying of the fine fuel layer. As a result, most of the fine fuel layer of the unburned forest requires more than 16 rainless days to dry sufficiently for ignition, but only 4% of heavily burned forests can resist fire for this long. More than 90% of the heavily burned forest can catch fire in less than 9 days of a rain event. Data from forests near Tailândia, Pará. Source: Cochrane and Schulze, in press.

3. Amazonia is Burning

After more than two decades of worldwide concern about fires in Amazonia, fundamental gaps in our understanding of these fires persist. What type of vegetation is burning? How large are the areas that are burning? How do the fires begin? In this chapter, we describe the state of our knowledge of these issues by synthesizing data from a variety of sources. We begin by describing satellite-based techniques for monitoring fires. In the following section, we propose a typology of Amazon fires and present the results of an extensive landholder survey conducted in 1996, designed to measure the areal extent of different types of burning, the variations in burning that are found with differing sizes of properties, and the economic aspects of fire. We close this chapter by incorporating the results of this study into an assessment of the ecological and economic impacts of Amazon fires.

3.1 Mapping fire from space

The Earth's surface is photographed two times every day by each of the NOAA[1] weather satellites orbiting 850 kilometers above the planet. Although these satellites were designed to provide information on weather patterns, they have emerged as the most important tool for monitoring fires over large regions such as Amazonia. The satellites register the energy that is being emitted by the land surface within various wave-lengths, including an infra-red wavelength (3.55-3.93

[1] These weather satellites are owned and operated by the US National Oceanic and Atmospheric Administration (NOAA), and carry a sensor which is called the Advanced Very High Resolution Radiometer (AVHRR).

mm) that can be used to estimate the temperature of the land surface. Since the main source of very high land surface temperatures is fire, the NOAA satellite data can be used to create daily maps of active fires when processed with computer software that records those areas where the temperature exceeds a threshold level (Setzer and Pereira 1991, Malingreau and Tucker 1988, Matson et al. 1984, Matson and Dozier 1981).

The fire maps that can be produced by the NOAA satellite data provide dramatic illustrations of the sheer magnitude of burning in Amazonia (Fig. 3.1), and are the cornerstone of the Brazilian government's program to monitor burning (Setzer et al. 1988). When we tally the total number of fires recorded by the satellites during the 1997 burning season (June through November), a zone of high burning frequency can be seen in eastern and southern Amazonia, where most Amazonian deforestation has taken place (Fig. 1.1). In some of the square picture elements (pixels) on this map,[2] 790 fires were registered in 1997 from an area of approximately 256 km^2 (16 x 16 km). This represents more than 3 fires per square kilometer! Fires were particularly common near Marabá in eastern Pará and Cuiabá in northern Mato Grosso.

While the NOAA sensors are the main source of "wall-to-wall" daily coverage of burning on a continental or global scale, the data that they provide are useful primarily as an index of fire intensity instead of as a direct quantitative measure of the number of fires, the area burned, or the type of vegetation that is burning. Since the data are

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[2] Each square on the map is called a picture element, or "pixel". In this map, the pixels of the original imagery, which are 1.1 x 1.1 km, have been combined into larger pixels of 16 x 16 km.

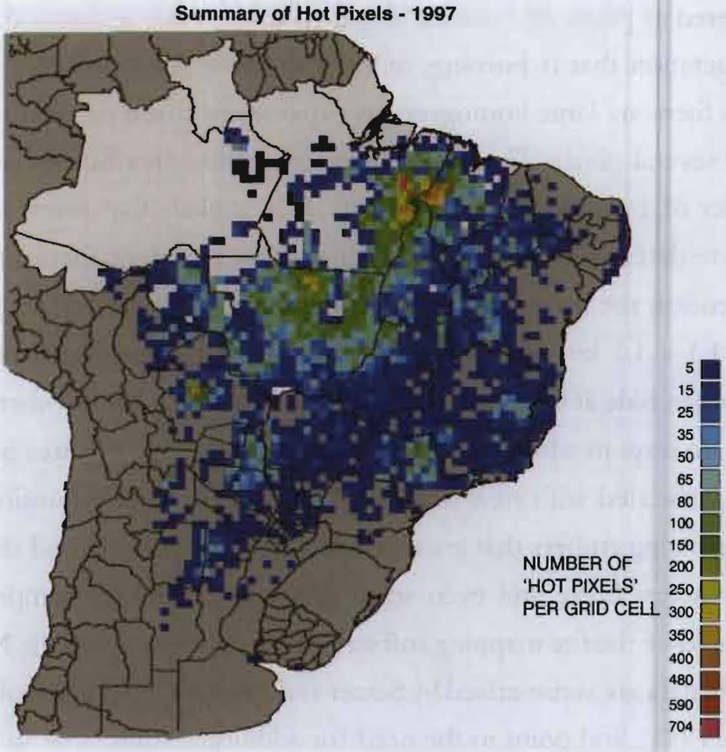

Figure 3.1 Fires' heat is detected by NOAA satellites, and registered to make daily fire maps. When these daily maps are added together, they show the concentration of Amazonian fires along the eastern and southern portions of the region. Such maps provide important information about the location of active fires, but say little about what is burning, whose land is burning, and what effects these fires have. Grid cells are 16 x 16 km (256 km²). Source: INPE.

registered as pixels of 1.1 x 1.1 km, it is not possible to know the type of vegetation that is burning, unless the fire is registered in a region where there are large homogeneous expanses of forest or pastures that cover several pixels. The data underestimate the area burned and the number of burns for several reasons. It is unlikely that forest surface fires are detected by this fire mapping technique, since these fires occur beneath the forest leaf canopy. Multiple fires occurring within the same 1.1 x 1.1 km pixel are registered as a single fire, and smoke or clouds can hide active fires from the satellite's view. On the other hand, there are ways in which the satellite data overestimate the area burned. Fires associated with new deforestation or with pasture burning may leave glowing embers that are registered as active fires beyond the time of the actual burn, and even small fires can exceed the temperature threshold of the fire mapping software. These limitations of the NOAA satellite data are summarized by Setzer and Pereira (1991) and Robinson (1989, 1991), and point to the need for additional sources of information.

More detailed information on Amazon fires is provided by the Landsat Thematic Mapper satellite of the US and the SPOT satellite of France. The pixels of these satellites (30 x 30 and 10 x 10 m, respectively) are much smaller than the 1.1 x 1.1 km pixels of the NOAA satellite, such that vegetation type can be determined either through visual inspection of the image, or through digital classification of the image, which identifies different vegetation types according to the amount of light that is reflected within up to seven classes of spectral wavelength. Since these satellites require 14-16 days to completely register the Earth's surface, they are not practical for monitoring active fires. Nevertheless, they are very useful for mapping the fire scars in vegetation. Forests that have suffered surface fires are easily distinguishable from unburned forests (Fig 3.2) because of the loss of leaves and the ash

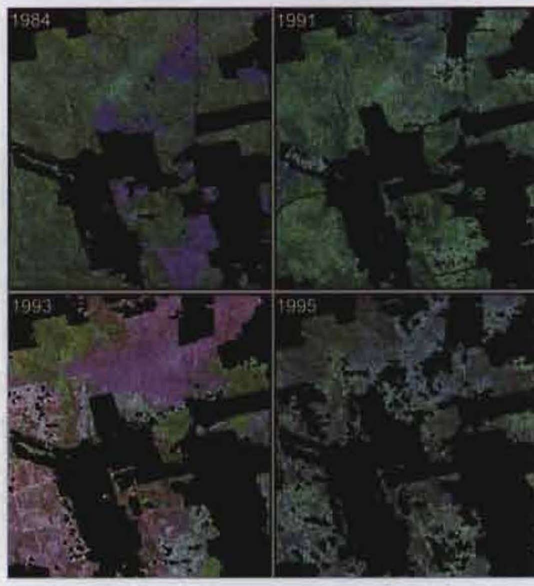

Figure 3.2 During the first year following forest surface fire, burn scars can be made visible on Landsat TM satellite imagery by using a special contrast enhancement technique. These four images of the same landscape near Paragominas, Pará, Brazil, over an 11-year period, show the cumulative degradation of forest due to forest surface fire, and the "disappearance" of forest burn scars in subsequent years. The 1984 and 1993 images show extensive scars (purple/pink) from fires provoked by drying associated with El Niño episodes in the prior years. Areas of pasture and other non-forested areas are black.

deposited on the soil. These scars are most easily seen within the first few months following the fire, before the vegetation has had a chance to reestablish its leaf canopy. However, forest fire scars can be detected for at least a year using remote sensing techniques (Fig. 3.2, Section 3.4).

But even high resolution satellite imagery such as Landsat TM and SPOT do not provide information on the landholders whose land is burning, the reasons for burning, and the economic impacts of burning. This type of information requires field research and interviews with landholders. We present here the results of five regional case studies of fire conducted in Amazonia in 1996. The description of this study is preceded by a review of the types of Amazonian fires.

3.2 Fire types

Any discussion of the Amazonian burning problem will depend upon a commonly accepted definition of the types of Amazon fires. Based on a review of the literature (Fearnside 1997, Hecht 1993, Homma 1998, Moran et al. 1994, Nepstad et al. 1991, 1997, Skole et al. 1994, Uhl et al. 1988a,b, Uhl and Buschbacher 1985, Walker and Homma 1996,) and our own field experience, we propose a fire typology of three main categories (Table 3.1):

• "Deforestation fires" are those associated with the clear-cutting and burning of standing forests in preparation for pasture formation, agricultural systems, or plantations.
• "Forest surface fires" burn the fuel layer on the floor of standing forests, either primary or logged.

Table 3.1. The major fire types of the Brazilian Amazon.

Type	What is burned	Why burned	Accidental
Deforestation fire	Logged and primary forest that has been clear-cut & dried	-Preparation for crops and cattle pasture	no
		-Land claim	no
Forest surface fire	Standing forest, logged & primary	-Unintentional	yes
Fire on deforested land	Degraded pastures	-Weed reduction	no
		-Unintentional	yes
	Secondary forest	-Preparation for crops or pasture	no
	Pasture	-Unintentional	yes
	Cropland, plantations	-Unintentional	yes

• "Fires on deforested land" include burns in pastures, secondary forests, croplands, and plantations.

It is also useful to further classify Amazon fires as "intentional" and "accidental". Deforestation fires are virtually all intentional, except for those that ignite at an unintended time of year. Forest surface fires, on the other hand, are mostly accidental, since landholders have little motive to burn standing forests. Forest surface fires are not, for example, a substitute for forest clear-cutting, since they leave behind many living trees in the forest. Deforested lands are intentionally burned when landholders set their pastures on fire to favor forage grasses over woody weeds, or when they cut down and burn secondary forests in preparation for crops or pasture formation. Accidental fires on deforested land occur when pastures, secondary forests, crops or plantations burn, either through the escape of intentional fires or through arson (Table 3.1).

In a land where the soil is infertile, the forest is abundant and cheap, labor and capital are generally scarce, the forest itself is the logical substitute for fertilizer. Each year, approximately 600 thousand poor families in the Brazilian Amazon cut and burn 1- to 3-hectare patches of forest to grow manioc, rice, corn, beans and other crops for subsistence and to sell in local markets (Homma 1997). The ancient practice of slash and burn agriculture permits the cultivation of crops in the acid infertile soils that dominate rural Amazonia by fertilizing the soil with the nutrient-rich ash of the burned forest (Fig. 3.3 a, b). The pulse of soil fertility that follows forest cutting and burning is temporary, however, and the rapid infestation of crop fields by weeds further reduces crop productivity. Crop yields often decline within one to three years of forest cutting and burning. A new slash and burn crop field is prepared annually by most poor farm families in Amazonia.

The slash and burn agricultural cycle starts early in the dry season when an area of forest is cut down using axes or chainsaws (Fig. 3.4a). Then the guessing game begins, as farmers try to allow their felled forests to dry as much as possible before the first rains of the wet season begin. If the cut forest is burned before it has thoroughly dried, the moisture content of the felled trees is high and large amounts of the forest biomass simply do not catch fire. A field prepared from a cut forest that has not dried thoroughly receives a smaller pulse of nutrient-rich ash, and a larger portion of the soil receives no ash input at all. As a result, crop yields are lower. An incompletely burned forest is also more difficult to work in because there are more felled trees and branches on the ground.

Figure 3.3 Amazon farmers practicing traditional slash and burn agriculture following forest felling and burning. (a) A family prepares the land for planting rice, the Del Rey Community, near Paragominas, Pará; and (b) a farmer showing some of his produce. (Photographs by M. M. Mattos (a) and D. Nepstad (b))

Figure 3.4 The initial phases of the slash and burn agricultural cycle. (a) The forested area is cut and allowed to dry. Some trees are left standing because they are useful to the farmer (for example, fruit trees), because they are dead and dangerous to cut, or because they harbor wasp nests. (b) Near the end of the dry season, the cut area is burned. The standing dead trees can catch fire, emitting sparks or falling into neighboring ecosystems. Del Rey Community, near Paragominas, Pará. (Photographs by Kátia Carvalheiro (a) and Daniel Nepstad (b))

Slash and burn fires (Fig. 3.4b) can easily escape into forests, pastures or crop fields that adjoin the area being burned. The tangles of dried, cut trees (Fig. 3.4a) send sparks skyward as they burn, and these sparks can become sources of new ignition. Trees left standing in the plot can also transmit fire into adjacent vegetation if they catch fire and fall. Slash and burn fires are also difficult to contain because labor is in short supply and subsistence farmers often cannot afford to cut firebreaks between their slash and burn sites and neighboring ecosystems.

Slash and burn agriculture can begin with either primary, logged or secondary forest (fallow forest on abandoned crop fields), with the vegetation of choice varying depending upon the availability of different forest types, distance to sawmills, the availability of labor, and the crop that is desired. Primary and logged forests require more labor to fell than do secondary forests, but require less labor for weeding during the subsequent growing season. Rice grows best on soils prepared from primary forest, while corn grows better on soils prepared from fallow forest (Toniolo et al., unpublished data). For the purposes of this discussion, deforestation fires refer to slash and burn agriculture that involves the clearing and burning of either primary forests or logged forests; the fires set as part of slash and burn agriculture in secondary forests are classified as "fire on deforested land".

Deforestation fires: pasture formation

Forests are also slashed and burned in preparation for cattle pasture formation (Hecht 1985, Serrão et al. 1979). The first step in converting forest to pasture is the felling, drying and burning of the forest. Only rarely is pastureland formed without the use of fire, since the input of ash to the soil is a large benefit of slash and burn techniques, and since slashing and burning are cheaper than clearing land with large bulldozers and chains. If cattle ranchers have access to bulldozers they often employ them to clear the residual charred trunks and branches from their land and scrape the surface soil and vegetation into windrows before planting pasture, facilitating planting and mechanized weeding. Yet many of Amazonia's rural producers, especially those with small land holdings, do not plant pasture immediately following forest felling and burning. Rather, they first plant subsistence crops (manioc, rice, beans, corn), then plant pasture grasses as crop productivity begins to fall off, or as the two-year cropping cycle comes to a close. In this way, they take better advantage of the pulse of nutrients going into the soil as ash, since crops generally require higher soil nutrient levels than pasture grasses. It is also common for landholders to sell the timber from their forest prior to pasture formation if they are located close to sawmills.

The deforestation fires associated with pasture formation, like those associated with crop production, are difficult to contain and often escape into neighboring forests, crop fields and pastures. The owners of large properties often have access to bulldozers, however, and therefore have the option of establishing firebreaks around their plots at a lower cost than those landholders who must make firebreaks manually (Section 3.7).

Forest surface fires

Standing Amazonian forests can catch fire during severe drought (Nelson 1994, Nelson and Irmão 1998, Nepstad et al. 1995, Sanford et al. 1985, Uhl et al. 1988a), following logging (Holdsworth and Uhl 1997, Uhl and Kauffman 1990, Uhl and Buschbacher 1985) and, presumably, following other forest disturbances that result in tree mortality, such as flooding (Nelson 1994, Nelson and Irmão 1998). Given the high humidity and the dense shade within forests, most of these fires burn slowly along the ground, consuming leaf litter, twigs and fine branches (Fig. 2.6). Fires that burn the leaf canopy of the forest, called "crown fires", are apparently rare events in Amazonia. Research is needed on the conditions under which crown fires could take place in Amazonia, since these fires are far more destructive of the forest than surface fires.

We are not aware of landholders who intentionally burn their standing forests, and assume in this book that forest surface fires are virtually all accidental. The use of surface fire as a post-harvest treatment in logging operations has been suggested by H. Knowles (personal communication) as a method for stimulating the rapid regeneration of commercially valuable pioneer tree species (e.g. *Jacaranda copaia*, *Schizolobium amazonicum*, *Didymopanax morototoni*), but has not been employed by commercial logging operations, nor has it been the topic of forestry research in Amazonia.

Fires on deforested land: pasture management

Burning for weed control: Burning is the cheapest way to favor the growth of pasture grasses over invading, unpalatable woody plants arising from root sprouts or seeds. The aboveground parts of woody plants are killed by fire, while grasses thrive after fire because their leaves grow upward from tissues buried just beneath the soil where they are protected from fire, and because their growth can be enhanced by the input of ash to the soil, and by the removal of their dry, dead leaves and stems (Hecht 1993). Hence, in the short term, burning reduces the coverage of woody plants and stimulates the growth of grasses.

Burning for pasture reform: Burning is frequently used by land managers as the first step in planting new forage, tilling and fertilizing the soil prior to planting. In the Paragominas region, the steps taken in reforming pastures are variable, but frequently include (a) burning to provide an input of ash to the soil; (b) bulldozing to remove the dead tree trunks that persist from the original cutting and felling of the forest, and to scrape away the weeds and surface soil into windrows (Fig. 3.5); (c) disk-harrowing the soil to further reduce weed populations and reduce soil compaction; and (d) fertilization and planting (Mattos and Uhl 1994, Nepstad et al. 1991). Farmers with less capital available often choose to reform their pastures by simply burning and reseeding.

But the low cost of combating pasture weeds with fire is offset by the potentially high costs of lost grazing time, lost fencing, lost nutrients, and the risk of burning ecosystems that adjoin the pasture. After a fire, pasture forage grasses must grow for 3 to 4 months during the rainy season before they can sustain grazing by cattle, and this "resting" period may be particularly important for *Brachiaria brizantha* ("braquiarão"), the forage species that is currently planted in greatest abundance in Amazonia. Pastures that are not burned can be grazed throughout the year. Fires can burn pasture fencing, and can escape into neighboring forests, crop fields and orchards. Moreover, in the long term, burning may greatly reduce the productivity of cattle pastures as nutrient shortages develop in the soil. When pastures burn, large amounts of nitrogen, phosphorus, and other pasture nutrients are released to the atmosphere through emissions of ash and volatilized nutrients (Buschbacher et al. 1988, Dias Filho et al., in press, Kauffman et al. 1995, 1998).

Figure 3.5 Cattle pastures are "reformed" in eastern Amazonia by scraping the weedy vegetation and soil surface into windrows with bulldozers, disk-harrowing, fertilization, and planting. The great majority of ranchers now plant Brachiaria brizantha *as a forage grass. Access to heavy machinery makes it easier for ranchers to avoid the use of fire for weed control. (Photograph by D. Nepstad, Fazenda Vitoria, Paragominas)*

The burning of weed-infested pasture and secondary forest also provides an important non-agronomic benefit to landholders by reinforcing the claim that they have on their land. An important criterion of land ownership in the Brazilian Amazon—both from a legal and practical perspective—is demonstration of productive utilization of the property. A ranch that is overgrown with secondary forest and has no cattle is more likely to be taken by the government for redistribution to the rural poor or invaded by squatters than is a ranch that has pasture and a cattle herd (Fearnside 1993, Hecht et al. 1988, Schmink and Wood 1992). Hence, the current structure of agrarian law favors the use of fire as an inexpensive way of defending claims on land.

Pasture fires often take place in large expanses of cleared land, where relatively high winds can impede fire control. The intensity and size of pasture fires are highly variable depending upon the status of the vegetation. Abandoned pastures, which have experienced little grazing and have abundant fuel, can generate flames >10 m in height and flaming air-borne embers that can be carried across firebreaks. Such pastures generally have few standing dead trees, and fires there can be contained by using firebreaks. Burning in abandoned pastures can also be contained by setting backburns, which are downwind fires set along the inside of the firebreak, allowing the vegetation to burn slowly, against the wind, effectively widening the firebreak (see Appendix II).

Fires on deforested land: accidental loss of anthropogenic ecosystems

Every year, many landholders of Amazonia suffer economic losses when fires inadvertently burn their pastures, crop fields, agroforestry systems, orchards, and plantations of oil palm, citrus, black pepper, cashew, cupuaçu, timber species and other perennial crops (Fig. 3.6). Accidental pasture fires may affect the largest area each year, because pasture itself is the dominant land cover on deforested land, but the importance of accidental fires in other agricultural and forestry production systems goes beyond their areal extent. For the annual threat of accidental fire signifies that returns on investments in these fire-sensitive forms of land-use may never be realized. In this sense, accidental fire provides a powerful disincentive to those rural producers who wish to intensify their production systems through economic investments in fire-sensitive agricultural and forestry production.

*Figure 3.6. This one-year old plantation of teak (*Tectona grandis*), established on a degraded pasture near Redenção, Pará State, was lost to accidental fire. The annual threat of burning discourages landholders from investing in fire-sensitive crops, such as timber trees. (Photograph by D. Nepstad)*

3.3 Property-level study of fire

Our understanding of fire in Amazonia is derived from two very disparate scales of analysis. At the scale of the entire region, we know the day to day occurrence of fires within 1.1 x 1.1 km squares of landscape as they are registered by the NOAA sensor (Fig. 3.1). From field studies, we know that each fire registered by the sensor may represent any one of a wide variety of fire types, which are profoundly different in their origin, and their ecological and economic effects. Clearly, an intermediate level of analysis is needed that provides information on the manifold types of burning in Amazonia, but at a regional scale. In an effort to fill this gap in our understanding, researchers at the Amazonian Institute of Environmental Research (IPAM) and the Woods Hole Research Center (WHRC) developed a method by which the history of fire on individual landholdings in Amazonia can be reconstructed. In 1996 we applied this method to a property-level investigation in five regions of Amazonia to determine the areal extension of four major types of fire, their causes, and some of the economic impacts of accidental pasture fire.

The design of a field study that accurately and quantitatively represents the full spectrum of fire occurrence is a formidable task in Amazonia. This vast region is a mosaic of frontier ages, marketing infrastructure, economic activities, property sizes, immigrant backgrounds, rainfall regimes, and forest types that defy a comprehensive sampling scheme. To provide a preliminary appraisal of the range of fire occurrence patterns as seen through property-level analysis, we selected five sub-regions in Amazonia that represent different combinations of these variables (Table 3.2). The locations selected include a major center of cattle and timber production (Paragominas), an area of giant ranches that are gradually being divided into smaller properties (Santana do Araguaia), a region with small colonization projects (Alta Floresta), two locations within the massive Polonoroeste colonization program of Rondônia (Ariquemes and Ouro Preto d'Oeste), and an incipient frontier linked to the rest of Amazonia by an all weather road in 1990 (Rio Branco) (Fig. 1.1). Each of the sub-regions has a seasonal rainfall regime, with a period of at least three months with less than 100 mm of rain per month (Fig. 3.7), and are therefore climatically typical of most of the region's expanding agricultural frontier; approximately 80% of the deforestation in the Brazilian Amazon has taken place in regions with a pronounced dry season (Fig. 1.1). The dominant forest formations included in this study are dense evergreen forest (Paragominas), open forest with palms and/or bamboo (Alta Floresta, Rio Branco, Rondônia) and forest in the transition zone from closed-canopy forest to savanna woodland ("cerrado") (Santana do Araguaia and Alta Floresta).

Table 3.2 Summary of properties studied.

	No	Size Category	Mean Area ± SE (há)	Total Area (ha)
All Sites Combined	53	Small	62±3	3,280
	66	Medium	414±33	59,456
	53	Large	2,525±158	140,011
	30	Very Large	24,334±5,653	745,630
Paragominas (NE of Pará)	7	Small	48±5	339
	26	Medium	523±57	13,610
	24	Large	2,862±362	59,967
	3	Very Large	24,841±10,355	83,236
Santana do Araguaia (S. Pará)	5	Small	84±7	421
	4	Medium	624±169	2,496
	3	Large	3,404±952	10,212
	10	Very Large	45,864±14,521	458,635
Alta Floresta (Mato Grosso)	9	Small	38±5	344
	6	Medium	233±36	1,399
	13	Large	2,578±312	33,519
	7	Very Large	9,254±861	64,781
Ariquemes (Rondônia)	12	Small	80±7	963
	15	Medium	343±61	5,152
	2	Large	1,928±22	3,856
	1	Very Large	5,360	5,360
Rio Branco (Acre)	20	Small	61±20	1,215
	15	Medium	312±178	4,679
	11	Large	2,159±653	23,745
	9	Very Large	15,814±17,953	142,330
Total	**202**			**916,257**

Small = 0-100 ha, Medium =101-1000 ha, Large = 1001-5000, Very Large = >5000 ha

Precipitation for Study Areas

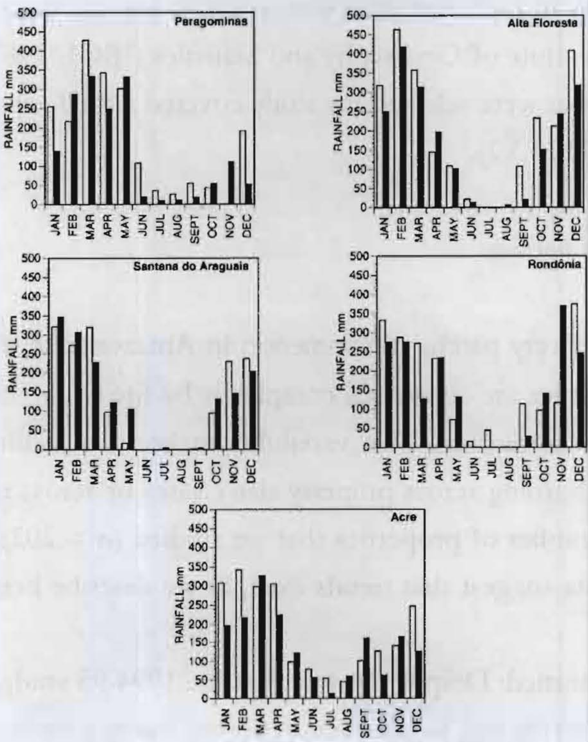

Fig. 3.7. Monthly rainfall in 1994 and 1995 for the five study areas of the property-level research. Each of the sites has a pronounced dry season, as is typical of the eastern and southern portions of Amazonia, where land-use activities are concentrated. Dry season rainfall was less in 1995 than in 1994 for Paragominas, Alta Floresta, and Rondônia.

Property maps were obtained for each sub-region,[3] superimposed upon satellite images (for example, Fig. 1.3) and used to randomly select properties to be studied. The selected properties were stratified among four different size classes to reflect the approximate distribution of property sizes of the sub-region. In each study sub-region, the number of properties in each size class was obtained for the county from the Brazilian Institute of Geography and Statistics (IBGE 1985). The 202 properties that were selected for study covered a total area of 916,257 hectares (Table 3.2).

How much is burning?

Burning is a very patchy phenomenon in Amazonia; in a given area, some properties are consumed completely by fire while other properties are left untouched. This variability makes it difficult to discern patterns in burning across property size classes or across regions with the small number of properties that we studied (n = 202). Nevertheless, our data suggest that trends exist, as we describe here.

Total area burned: Despite the fact that the 1994-95 study period was not exceptionally dry, landholders reported burns covering 77,000 ha per year, which is 8.4% of the combined area of the properties studied (916,257 hectares, Table 3.3). The calculation of the percentage of the land that burned each year in the study area may appear straightforward, but in fact requires some further consideration. For example, when we estimate burning as the average of the rates reported by each landholder, the overall rate of burning climbs to values of 8 to 20%, depending upon the region and year (Table 3.4). The rate of burning is

[3] We obtained property maps from local government offices or from the headquarters of the colonization programs.

greater when calculated in this way because the percentage of each property that burns each year decreases with increasing property size, as we discuss below.

Out of every ten property managers interviewed, between five and eight reported a fire on their property in a given year, depending on the region and year (Table 3.5). And yet, the actual area that burned, and the percentage of properties that experienced fire, may be much larger than that reported by the landholders interviewed, since most of these fires were unlicensed and could lead to fines or imprisonment. The landholders had strong incentives to conceal this information.

The number of properties that experienced fire was higher in 1995 than 1994 for all but one of the study regions; an average of 62% of landholders reported fire of some type on their land for 1994 and 76% for 1995 (Table 3.5). The occurrence of fire was not, however, a function of property size. The percentage of interviewed landholders who reported fire on their property ranged from 60 to 71% across size classes in 1994, and from 71 to 83% in 1995 (Table 3.6). Within all property size classes, more than 80% of the properties studied caught fire during the combined two-year period.

Fire type: Deforestation fires—the fires associated with the cutting and burning of primary or logged forest in preparation for agriculture and pasture formation—affected 9,800 hectares each year, which is 1.1% of the combined study area (Table 3.3). The average of deforestation burning reported by each landholder was twice as high (2.3% per year, Table 3.7), however, since the large landholdings experienced a lower rate of deforestation burning than small properties. Approximately one fourth to one third of the landholders reported deforestation fires each year (Table 3.8).

Table 3.3. Total sample area and total area burned by fire type and year, for the property-level study of fire occurrence described in the text. n = 202 properties.

	1994		1995		Mean 94-95	
	hectares	% of total sample area	hectares	% of total sample area	hectares	% of total sample area
Total sample area:	916,257	100	916, 257	100	916, 257	100
Total area burned:	74,940	8.2	78,220	8.5	76,580	8.4
Total area burned by fire type:						
Deforestation fire	9,790	1.1	9,830	1.1	9,810	1.1
Forest surface fire	18,280	2.0	12,630	1.4	15,450	1.7
Deforested land, intentional	9,010	1.0	21,530	2.4	15,270	1.7
Deforested land, accidental	37,860	4.1	34,240	3.7	36,050	3.9

Table 3.4 The mean percentage of each of the properties studied that burned in 1994 and 1995 for five regions of Brazilian Amazonia.

		Percentage of Each Property Burned Mean ± SE		
Region	n	1994	1995	1994-95
Paragominas	60	12.1 ± 2.7	18.9 ± 3.1	15.5 ± 2.9
Santana do Araguaia	22	8.4 ± 2.2	13.9 ± 4.4	11.2 ± 2.7
Alta Floresta	35	8.5 ± 2.4	13.7 ± 4.0	11.1 ± 2.3
Ariquemes	30	9.3 ± 3.3	14.7 ± 3.4	12.0 ± 3.3
Rio Branco	55	13.6 ± 2.9	19.5 ± 3.5	16.5 ± 3.0

Table 3.5. The percentage of the interviewed landholders who reported fire on their land in 1994 and 1995, by region.

		Percentage of Landholders		
Region	n	1994	1995	Mean 1994-95
Paragominas	60	58	75	66
Santana de Araguaia	22	73	73	73
Alta Floresta	35	51	66	58
Ariquemes	30	53	80	67
Rio Branco	55	75	84	80
Average of Regions	202	62	76	69

Table 3.6. The percentage of the interviewed landholders who reported fire on their land in 1994 and 1995, by property size.

Property Size (ha)	n	Percent of Landholders 1994	1995	1994 or 95
Small (<100)	53	60	74	83
Medium (101-1000)	66	59	76	86
Large (1001-5000)	52	62	83	92
Very Large (>5000)	31	71	71	84

Table 3.7. The mean percentage of each property area burned each year by the four fire types, and the area burned by each fire type as a percentage of the total area burned, for five study regions in the Brazilian Amazon. Data for 1994 and 1995.

	Deforestation Fire	Forest Surface Fire	Deforested Land, Intentional Fire	Deforested Land, Accidental Fire
	Mean ± SE			
Percent of Property	2.3 ± 0.6	0.9 ± 0.3	6.8 ± 1.0	4.2 ± 0.9
Percent of Total Area Burned	13	8	47	33

Table 3.8. The percentage of the landholders who reported fire on their land in 1994 and 1995, by property size and fire type.

Property Size (hectares)	n	Deforestation Fire 1994	Deforestation Fire 1995	Forest Surface Fire 1994	Forest Surface Fire 1995	Deforested Land, Intentional Fire 1994	Deforested Land, Intentional Fire 1995	Deforested Land Accidental Fire 1994	Deforested Land Accidental Fire 1995
Small (<100)	53	32.1	22.6	1.9	7.5	35.8	45.3	15.1	30.2
Medium (100-1000)	66	27.3	22.7	6.1	12.1	34.8	45.4	15.1	39.4
Large (1001-5000)	52	30.8	25	6.1	12.1	30.8	46.1	21.1	42.3
Very Large (>5000)	31	29	35.5	9.7	9.7	25.8	29	29	35.5
Combined	202	29.7	25.2	5.9	11.4	32.2	43.6	17.8	37.1

%One of the most important discoveries of this study was the widespread occurence of forest surface fire. Landholders in Santana do Araguaia, in southern Pará, reported surface fires averaging 1300 hectares per property each year! Among the combined properties, a total of 15,500 ha of standing forest were burned by surface fire each year representing 1.7% of the study area (Table 3.3), which is 50% more forest than that affected by deforestation. The rate of burning through forest surface fire declines when expressed as the average percentage of each property, because the rate of this type of burning is higher on larger properties than on smaller properties. Across all of the regions and properties, these fires burned an average of 0.9% of each property annually (Table 3.6), and comprised 8% of the average area burned per property (Table 3.7).

Forest surface fires affected a smaller percentage of the properties than other types of fire. Only 2 to 12% of the landholders surveyed reported forest surface fire on their land in any given year, or within any of the size-class categories, compared to 25 to 35% who reported deforestation fires, and 26 to 45% who reported intentional fires on deforested land (Table 3.8). A single forest surface fire in 1994 burned 14,500 hectares, which is 80% of the total area of this type of fire reported for that year (Table 3.3). This single fire affected 1.5 times more forest than all of the deforestation fires for that year combined (Table 3.3)! The episodic nature of forest surface fire makes statistical analysis difficult. A larger number of properties must be studied to more accurately describe the areal extent of surface fire in standing Amazonian forests.

Surface fires in logged forests have been reported previously in the Paragominas region (Uhl and Buschbacher 1985, Holdsworth and Uhl 1997), and surface fires in primary forests have been observed by Nelson

(1994). But our study is the first to show that this type of fire can affect very large areas of forest each year, particularly in southern Pará (Santana do Araguaia) and Mato Grosso (Alta Floresta), where approximately half of the forest surface fires were in primary forest. While ~1.7% of our study area experienced surface fire each year, Nelson (1994) found that only 0.01% of Amazonian forests (approximately 50,000 hectares in all of Amazonia) had experienced forest surface fire, based on analysis of Landsat TM imagery for 1984. There has either been a dramatic increase in the area of forest that is affected by surface fire from 1984 to 1994, or the scars of many forest surface-fires are difficult to discern from paper prints of Landsat TM images. While both factors are probably relevant, forest surface fires are clearly on the rise.

Burns on deforested land affected far more land each year than either deforestation fires or forest surface fires. Approximately 5.6% of the combined study area was affected each year by fire on deforested land, compared to 1.1 and 1.7% for deforestation and forest surface fire, respectively (Table 3.3). When calculated as the average of burn rates reported by landholders, fires on deforested land affected 11% of each property per year, and represented an average of 80% of the area burned per property (Table 3.7).

Of the 51,000 hectares of deforested land that burned each year in the combined study area, only 30% was described as "intentional" by the landholders we interviewed. The remaining area of deforested land that burned (70%) was described as accidental, and represents nearly half (47%) of the entire burn area on the combined study area (Table 3.3). If we include forest surface fires as accidental burns, then two thirds of the area burned on the study properties was unintentional—desired by no one.

The average rate of burning per property was higher for intentional fires on deforested land (6.8%) than for accidental fires (4.2%), however (Table 3.7), because accidental fires were more common on large properties. Each year, an average of 35% of the properties studied experienced an accidental fire on deforested land, while an average of 29% of the landholders set intentional fires on deforested land (Table 3.8). It is not surprising that 95% of the area of deforested land that burned each year was by pasture fires. Pastures are the most common type of agricultural vegetation on deforested land, and they can be ignited within a day or two of a rain event during the dry season (Uhl and Kauffman 1990).

Property size: The rural properties that we studied, like rural properties across Amazonia, span an enormous range of sizes, from 10 to 148,000 hectares! This variation in size demands a differentiated analysis of fire, because the subsistence farmer struggling to make a living on one of the smallest properties employs fire in a much different way than the large-scale rancher who inspects his holdings from an airplane.

The pattern of annual burning across property sizes has several important features. First, the average owner of a very large Amazonian ranch burns 1800 hectares of vegetation each year, which is roughly 130 times larger than the area burned by the owner of a small farm (Fig. 3.8b, Appendix I). In the case of forest surface fire, the large-scale rancher burns an average of 440 hectares each year, compared to one hectare of forest burned by the smallholder (Appendix I). But given the vast size of large-scale ranches in Amazonia there is a four-fold reduction in burning with increasing property size when annual burning is expressed as a percentage of property area (Fig. 3.8a, Table 3.9). The most important fire type in accounting for this difference is fire on deforested land, which declines from 11% of the property area on

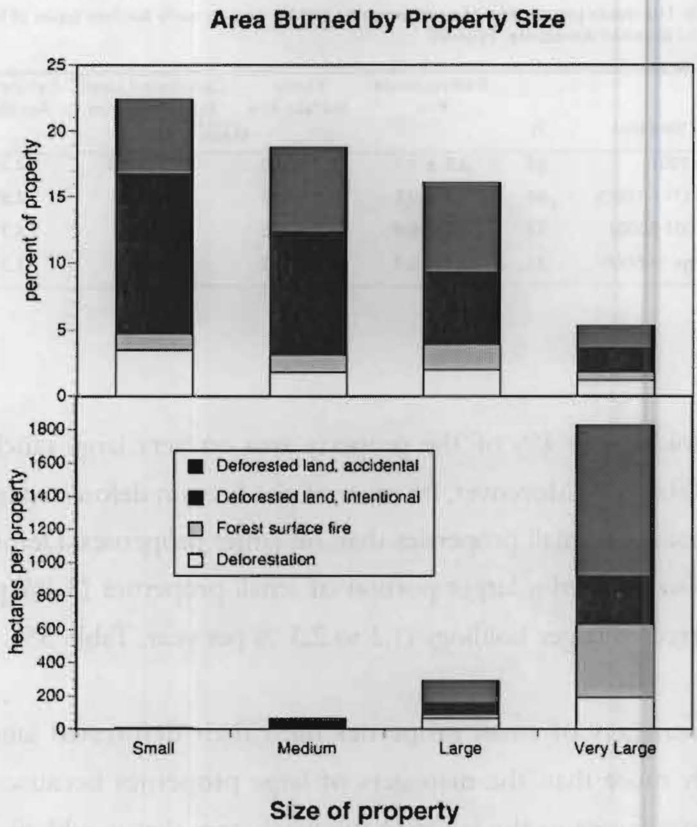

Fig. 3.8. The areal extent of four types of fires on 202 properties distributed among five locations on the Amazon frontier, as reported by landholders. The data are presented within four property size-classes: Small (<100 hectares), Medium (101-1000 ha), Large (1001-5000 ha), and Very Large (>5000 ha). When the area burned is expressed as a percentage of property size, it appears that small properties (<100 hectares) burn more than large properties (a). In absolute terms, however, (hectares per property), large-scale landholders burn far more than small-scale landholders (b).

Table 3.9 The mean percentage of each property that burned annually for four types of fire in five regions of Brazilian Amazonia, 1994-95.

Property Size (ha)	n	Deforestation Fire	Forest Surface Fire	Deforested Land, Intentional Fire	Deforested Land, Accidental Fire
		Mean ± SE			
Small (<100)	53	3.3 ± 1.1	0.7 ± 0.3	11.3 ± 2.4	4.2 ± 1.3
Medium (101-1000)	66	2.3 ± 0.5	1.1 ± 0.6	8.1 ± 1.6	4.9 ± 1.3
Large (1001-5000)	52	2.0 ± 0.6	1.1 ± 0.6	3.9 ± 0.9	4.7 ± 1.3
Very Large (>5000)	31	1.3 ± 0.4	0.8 ± 0.3	1.2 ± 0.6	1.7 ± 0.6

smallholdings to 1% of the property area on very large ranches (Fig. 3.8a, Table 3.9). Moreover, far more of the fires on deforested land were intentional on small properties than on larger properties. Deforestation fires also affected a larger portion of small properties (3.3% per year) compared to larger holdings (1.3 to 2.3 % per year, Table 3.9).

The managers of small properties burn their deforested land intentionally more than the managers of large properties because they do not have access to the labor or the machinery that would allow them to control weeds in their pastures without fire. Eight out of ten small properties were burned for weed control in 1994 and 1995, while only 4 to 6 in ten large properties were burned for this same purpose. In contrast, half of all large and very large properties employed tractor-drawn mowers to control pasture while only 3% of small property holders reported the use of mowing.

Accidental fires on deforested land affected an average of 4 to 5% of each property per year except on very large properties, where it affected less than 2% (Table 3.9). Property owners in all size classes reported that most of their accidental fires originated from clearing on neighboring lands. The owners of very large properties reported that only 3% of their deforested area that burned accidentally had originated on their land, vs. 28% for owners of small properties (Fig. 3.9). The most important off-site cause of these accidental fires cited was fire from pastures on neighboring land, fire from deforestation burns on neighboring land and fire started along roadsides (Fig. 3.9). Here, again, it must be remembered that landholders had a strong incentive to say that their accidental fires were not their fault because they knew that responsibility for such fires might bring fines. There is no incentive that we can think of for landholders to admit responsibility for accidental fires other than the desire to be honest.

3.4 Burning across Amazonia

An assessment of the ecological and economic impacts of Amazonian fires depends upon an understanding of the areal extent of each fire type. Analysis of possible solutions to the Amazonian burning problem requires information on the types of properties which are responsible for the burning. In this section, we summarize knowledge of the areal extent of each type of burning across Brazilian Amazonia by integrating estimates based on satellite imagery and our property-level studies.

Deforestation fires

Despite the fact that deforestation fires represent only one eighth of the total area burned on the properties that we analyzed (Table 3.3), this is the only type of burning in which the end result (deforestation) is consistently monitored. Deforestation monitoring is widely accepted as a comprehensive measure of human impacts on Amazonian forests, even though it does not include those areas of forest that have experienced surface fire or that have been selectively logged. Our stud-

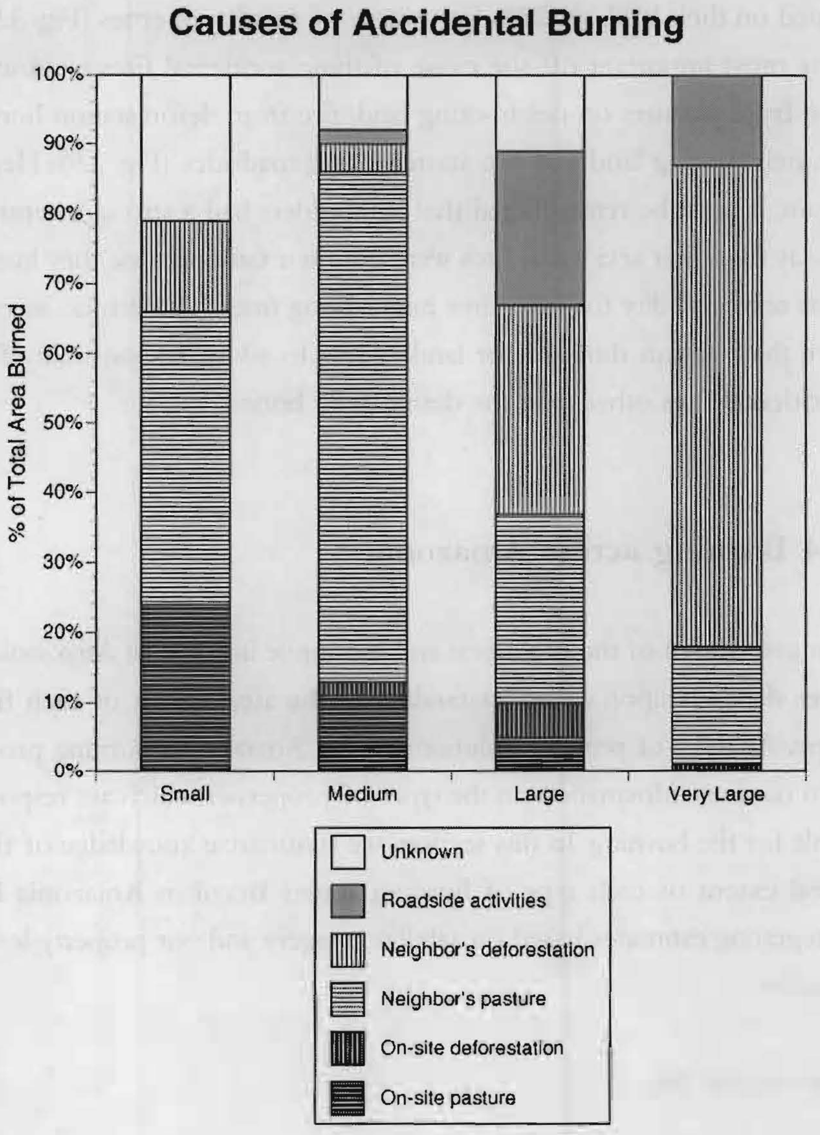

Fig. 3.9. The origins of accidental fires as reported by land holders during 202 interviews distributed among five locations on the Amazonian frontier. The vast majority of the area accidentally burned was attributed to off-site sources, including roadsides, neighbors' deforestation burning, and neighbors' pasture burning.

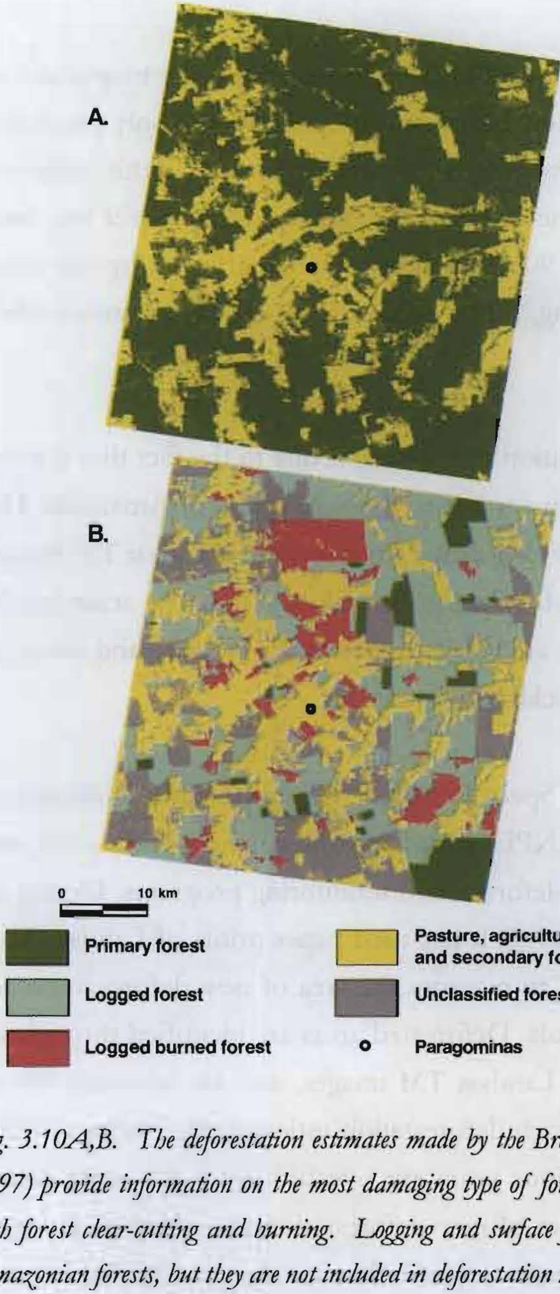

Fig. 3.10A,B. The deforestation estimates made by the Brazilian Government (INPE 1997) provide information on the most damaging type of forest burning: that associated with forest clear-cutting and burning. Logging and surface fires also profoundly affected Amazonian forests, but they are not included in deforestation mapping exercises. In the top Landsat image (A), the Paragominas region is mapped as deforested (yellow) and forested (green), using the techniques employed by INPE (INPE 1997). This analysis estimates that 66% of the Paragominas region still supports forest. When data from landholder interviews and logging scars mapped using Landsat imagery are added to this image, we see that very little of the primary forest remains: approximately 6%.

ies conducted in the Paragominas region illustrate the magnitude of the errors that arise when deforestation is used as the only parameter for measuring human impacts on Amazonian forests. In this cattle and logging center, only one third of the original forest cover has been cleared yet more than 90% has been severely affected by the combined impact of logging, forest surface fires, and deforestation (Box 3.1, Fig. 3.10a,b).

This focus on deforestation monitoring is due to the fact that it is the easiest type of forest conversion to measure for all of Amazonia. Deforested land is easily distinguished from forest in Landsat TM images even years after the deforestation has taken place. The scars left by fires in standing forests are harder to detect (Figure 3.2), and those on deforested land are quickly overgrown.

The Brazilian National Space Research Agency (Instituto Nacional de Pesquisas Espaciais—INPE) maintains one of the world's most ambitious and successful deforestation monitoring programs. During almost every year since 1988, it has used paper prints of Landsat Thematic Mapper images[4] to measure the area of new deforestation for all of Brazilian Amazonia. Deforested areas are identified through visual inspection of the Landsat TM images, and are manually traced onto clear paper. For each deforestation estimate, the tracings of deforestation from previous years are overlaid upon the most recent Landsat image and areas of new deforestation are added to the tracing. These new patches of deforestation are digitized and added to a computer database, and their area is estimated within a Geographical Information System.

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[4] *These images are processed at a scale of 1:250,000, meaning that a kilometer is equivalent to four milimeters on the image.*

By the end of 1996, approximately 517,000 km^2 of closed canopy forest in Brazilian Amazonia had been clear cut and burned, representing 13% of the original area of closed-canopy forest (4,000,000 km^2) (INPE 1997). This deforested area is ten times the size of Costa Rica. Since 1978, the average annual deforestation rate for the Brazilian Amazonia is 19,000 km^2 with a reduction of deforestation from 1990 to 1993 and an abrupt increase from 1994 to 1995 (Fig. 3.11). This latest increase in deforestation is difficult to understand since there were no major political or economic changes at this time which might explain a two-fold increase in deforestation. The plummeting price of land following implementation of the Brazilian "Plano Real" in July 1994 may have been associated with this increase in deforestation. It is also surprising that we did not find a significant increase in the area of deforestation from 1994 to 1995 based on our property-level interviews (Table 3.3, 3.8).

Because the INPE deforestation estimates are based upon measurements of individual patches of newly deforested land—and not on the cumulative area deforested—they provide only indirect information on the contribution of different property sizes to total deforestation. It is impossible to assess the contribution of very small properties (<100 ha) to deforestation from these data because deforestation patches of less than 6 hectares are virtually impossible to detect in the 1:250,000 scale images employed by INPE for this mapping effort. In our study we found deforestation averaged 3.3 percent of properties less than 100 hectares in size (Table 3.9).

Forest surface fires

Despite an early report (Uhl and Buschbacher 1985) of the 'disturbing synergism between logging and forest fire', little information is avail-

Box 3.1. Cryptic impoverishment of Amazonian forests through forest surface fire and logging: the case of Paragominas.

How do we measure the influence of human activities on the forests of Amazonia? Deforestation rates have become a widely accepted parameter for monitoring this influence, but they miss many of the effects people are having on the forests. Logging crews operating beneath the canopy fell and damage trees, increasing forest vulnerability to surface fires which kill large numbers of trees and animals, and which increase the likelihood of further burning (Section 2.4 and 3.6). But both logging and surface fire are excluded from the Brazilian program for monitoring deforestation, described in Section 3.4. We illustrate the problems that arise when logging and surface fire are omitted from tropical forest monitoring programs by combining the information on logging and forest surface fires acquired through our property-level study with information acquired from satellite imagery for the Paragominas region, in eastern Amazonia. In this 30-year-old frontier region, the deforestation monitoring technique employed by INPE would conclude that one third of the Paragominas landscape has been deforested (Fig. 3.10a). However, when we map those areas of forest that have been logged or burned by surface fire, we find that 94% of the forests of this region have been severely affected by human activity and are highly vulnerable to accidental forest fire (Fig. 3.10b, Nepstad et al., in press). In other words, the government's deforestation estimate would capture only one third of the forest area severely affected by human activities in the Paragominas region.

The impoverishment of forests through logging and burning is not peculiar to the Paragominas region. IMAZON recently completed a study involving 1393 interviews of sawmill operators in 75 regional logging centers in all of the states of the Brazilian Amazonia. This study, which accounts for more than 90% of the timber production in the region, concluded that approximately 10,000 to 15,000 km^2 of forest are logged each year (Nepstad et al., in press). Forest surface fires were detected on properties across Amazonia in our property-level survey, affecting an area that is roughly equivalent to the size of the total area deforested each year (Nepstad et al., in press). These "cryptic" forms of forest impoverishment will increase our estimates of carbon emissions to the atmosphere.

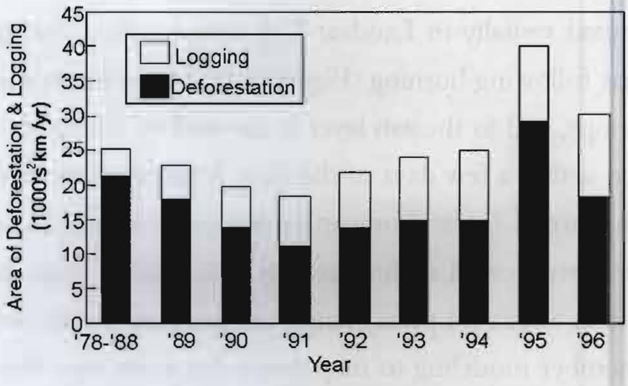

Fig. 3.11. Deforestation in Brazilian Amazonia, as reported by INPE. We have added an estimate of the forest area subjected to logging to illustrate the contribution of this forest alteration to the estimate of forest area affected by human activities each year. This logging rate was estimated based on sawmill interviews in 1996 and 1997, and we assume here that the rate of logging increased 10% each year until this time. Source: INPE 1997, Nepstad et al., in press.

able on the areal extent of this very important alteration of Amazonian forests. Our analysis of the area of Amazon forest that is vulnerable to surface fire in 1998 illustrates the potential magnitude of this type of fire (Chapter 4). We estimate that approximately 200,000 km^2 of forest were at very high risk of burning by the end of the 1998 dry season (that is, had depleted all of the plant-available water in the upper five meters of soil), which is ten to fifteen times the total area deforested each year. In a scenario of increasingly frequent El Niño events, Amazonia is poised to experience catastrophic forest fire events that dwarf the fires of Roraima in early 1998 and of deforestation activity in scale.

Mapping of past forest surface fires is possible but more difficult than deforestation mapping. Forest surface fires provoke leaf shedding, kill trees, and leave a layer of ash on the forest floor, and are therefore easily detected visually in Landsat TM images taken during the first few months following burning (Figure 3.2). As the forest reestablishes its leaf canopy, and as the ash layer is covered by falling leaves (which can happen within a few days of the fire), it becomes more difficult to distinguish burned forest from unburned primary and logged forest, and more sophisticated techniques are required to map these scars. Cochrane and Souza (in press) employed a technique known as spectral end member modeling to map forest fire scars near Paragominas. This technique separates the Landsat TM image information into physically meaningful elements and is capable of detecting the fractional increase of dead vegetation and exposed soils within burned forests. This technique has not been applied to large regions of Amazonia, but would be a very useful addition to INPE's current monitoring of deforestation in Amazonia.

Our property-level analysis of burning provides another means for estimating the areal extent of forest surface fires. In the 9,160-km^2 sample area of this study, which is approximately 0.25 % of the Brazilian Amazon, a total of 150 km^2 of forest surface fire were reported, which represents an average of 1.5 hectares of standing forest burned in 1994 and 1995 for every hectare of forest that was deforested (Table 3.3). If this ratio is applied to the INPE estimates of deforestation for the Brazilian Amazon in 1994 and 1995, we estimate that approximately 30,000 km^2 of standing forest burned during each of these years. This estimate is preliminary since the variability of surface fires is so high among properties. Approximately half of the total area of forest surface fires reported in our study was a single burn on a large ranch in Santana do Araguaia. Even if we remove the very high rate of forest surface fire measured in Santana do Araguaia, our estimate of the area of surface per year is 13,000 km^2 yr^{-1}. A broader study of the occurrence of such large forest surface fires is needed to establish a reliable estimate of this type of burning.

Fires on deforested land

Each year, enormous areas of deforested land burn in Amazonia. Setzer and Pereira (1991) used NOAA hot pixel data to estimate that more than 100,000 km^2 of deforested land burned in 1987 in Brazilian Amazonia, which is five times larger than the average area deforested each year (Figure 3.11). The property-level study also showed that for every hectare of forest that was cut and burned, approximately five hectares of deforested land caught fire (Table 3.3, Appendix I).

Beyond this overall magnitude of fire on deforested land, there is very little information about this type of burning available for the entire region. We do not know how much of this burning takes place in pastures and secondary forests, which are the two most common vegetation types on deforested land. Nor do we know the frequency with which deforested lands are re-burned. This type of information could be acquired through analysis of Landsat satellite imagery acquired at the end of the burning season, or early in the rainy season, before the burn scars are covered by regrowing vegetation.

3.5 Whose land is burning?

One of the most controversial issues in the debate about Amazonian conservation is where to place the "blame" for deforestation. This debate—like many others in Amazonia—is hampered by an overly simplistic, "binary" approach, which is summarized in the question:

are poor, subsistence farmers the culprits, or are large-scale ranchers to blame? To attempt to answer this question would be to give it a legitimacy which it does not deserve, for virtually all rural producers in Amazonia cut and burn their forests, and the rate at which they do so varies by year, by region and by the type of agricultural production that is practiced.

The property-level study illustrates the fact that deforestation occurs on properties of all sizes and, hence, can be attributed to producers ranging from slash and burn farmers to extensive cattle ranches (Figure 3.8a,b). We used these data to calculate the relative contribution of different property sizes to deforestation in the five regions that we studied by multiplying the average annual deforestation rate for each of four property size classes by the land area of the municipality contained within that property size class, based on the agricultural census (IBGE 1985). This analysis indicates that approximately one fifth of deforestation took place on small properties (<100 ha) in 1994 and 1995 in the five regions studied (Figure 3.12).

When we extend this analysis to the three other types of fire, we find that only eight percent of the total area of forest surface fires occur on small properties (Fig. 3.12). Small-scale farmers may invest more in the prevention of forest surface fires than large-scale producers because they depend upon the forest as a source of wild game, fruits, medicines, and building materials. The economic value of forests to large-scale landholders is generally restricted to timber, so that logged forests have little economic value and are not "worth" defending from accidental fire.

In contrast, nearly one third of the area of intentional burning on deforested land occurred on properties of less than 100 hectares in size

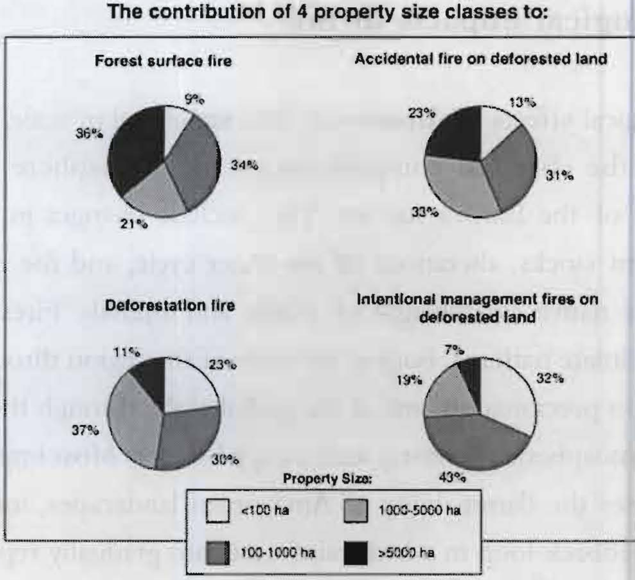

Fig. 3.12. The relative contribution of four property-size classes to the areal extent of four fire types. To determine these levels of contribution, the average percentage of each property size class that burned for each of the four fire types was multiplied by the total area occupied by that property size class within the study sample.

in the five regions studied (Figure 3.12). This relatively large value reveals the dependence of small-scale landholders on fire as a management tool.

Research is needed to determine which kinds of production systems are most likely to use fire, and the conditions that favor the greatest investment in fire control and prevention—both for fire risk assessment and for targeting governmental initiatives to reduce fire. Other than property size, a wide range of factors may be significant, such as land tenure status, land productivity, distance to market, absenteeism, capital investment, and duration of settlement.

3.6 Ecological impacts of fire

The ecological effects of Amazonian fires are global in scale, for they influence the chemical composition of the atmosphere and the reflectivity of the Earth's surface. They include changes in biomass and nutrient stocks, alterations of the water cycle, and the impoverishment of native assemblages of plants and animals. Fires may be affecting climate patterns, both at the scale of the region through their influence on precipitation, and at the global scale, through their influence on atmospheric chemistry and energy balance. Most importantly, fire increases the flammability of Amazonian landscapes, initiating a positive feedback loop in which rainforests are gradually replaced by fire-prone vegetation.

The ecological importance of each fire type is a product of its areal extent and the impact per area burned. In this integrated assessment, we find that deforestation and surface fires in forests are far more important ecologically than fires on deforested land, even though they affect only one fourth the area.

Deforestation fires

Deforestation fire, which involves the clear-cutting and burning of Amazon forests, is the most dramatic form of forest alteration by people. Deforestation fires kill all aboveground plant tissues in the forest, they kill or drive away forest animals, and they release forest nutrients and carbon contained in biomass into the atmosphere. By killing aboveground tissues, deforestation fire interrupts the flow of water into the atmosphere via evapotranspiration and exposes the soil surface to the erosive action of rain and wind. Because of the extremity of its ecological effects, deforestation fire is frequently viewed as the only fire type that is ecologically important (Box 3.1). For example, estimates of the carbon released to the atmosphere through human activity in Amazonia are based solely on the area of annual deforestation multiplied by the amount of carbon stored in the vegetation released to the atmosphere through clearcutting and burning (e.g. Fearnside 1997, Schroeder and Winjum 1995). These studies estimate that the net carbon release from Amazonia is 0.3 billion tons of carbon to the atmosphere each year, or is 4 % of the annual global flux of carbon to the atmosphere caused by all human activities.

The ash-covered soil left behind by deforestation fires is quickly covered by new plant growth as agricultural systems are established, or as forest recovery takes place. The long-term ecological impact of deforestation fire therefore depends upon the type of vegetation that replaces the forest once it is clearcut and burned. The most common type of vegetation on deforested land is comprised of African forage grasses (in particular, species of the genera *Brachiaria*, *Panicum* and *Andropogon*) planted for cattle production. The second most common type of vegetation on deforested land is secondary forest. We discuss the ecological impacts of deforestation by comparing these two vegetation types with the forests that they replace.

Rainforest conversion to pasture is one of the most radical alterations of native biota in human history. When a hectare of Amazon forest is deforested, burned and converted to cattle pasture, populations of hundreds of native plant species and thousands of animal species are replaced by a mono-dominant stand of African forage grass (e.g. *Brachiaria brizantha*), an imported species of ungulate, an ant fauna dominated by voracious seed- and plant-eating species, and communities of generalist bird and mammal species (Moutinho 1995, 1998, Nepstad et al. 1996 a,b, 1991, 1995, 1997, Silva et al. 1996, Vieira et al. 1996). The 300-ton forest is replaced by a ten-ton grass field—a field which reflects 50% more solar radiation back into space, and which releases 10-20% less water to the atmosphere through evapotranspiration (Jipp et al. 1998, Nepstad et al. 1994, 1995, Salati and Nobre 1991, Uhl et al. 1988a, Wright et al. 1992). Because they release less water vapor to the atmosphere than the forests they replace, cattle pastures generate greater runoff, which exacerbates stream flooding and provokes soil erosion. This is true because dry season evapotranspiration in forests dries out the soil, increasing the soil's sponge-like capacity to retain rainwater during the subsequent wet season, thereby reducing the amount of run-off to streams. Surface run-off water is the most important agent of soil erosion. Climate models predict that, because of these changes in energy and water balance, large-scale forest conversion to pasture may lead to a reduction in rainfall and an increase in temperature in the region (Nobre et al. 1991, Shukla et al. 1990).

Secondary forests are common in Amazonia because many of the cattle pastures and agricultural fields established following deforestation are eventually abandoned (Walker and Homma 1996, Serrão and Toledo 1990, Uhl et al 1988b). Indeed, field abandonment and subsequent secondary forest regrowth are an integral part of the slash and burn agricultural system that sustains small-scale farmers across Amazonia (Moran et al. 1994, Skole et al. 1994, Uhl et al. 1988b). Land abandonment initiates a process of forest regrowth that gradually recovers some of the functional and structure characteristics of the primary forest. The rate of this recovery depends upon the type of land-use practiced prior to land abandonment. Forest recovery is rapid following slash and burn agriculture, and slower following pasture abandonment. When pastures are used heavily through overgrazing, repeated burning, bulldozing or herbiciding, forest recovery can be arrested for several years following abandonment because of the shortage of tree seeds, heavy predation of newly arrived seeds by ants and rodents, competition with weedy vegetation, and drought (Nepstad et al. 1991, 1996a, 1996b, Silva et al. 1996, Uhl et al. 1988b, Uhl et al. 1989, Vieira et al. 1996).

Following deforestation, regenerating secondary forests recover hydrologic functions rapidly. A fifteen-year-old secondary forest in Paragominas had the same rate of evapotranspiration as a neighboring primary forest (Jipp et al. 1998). The recovery of biomass and species composition is a much slower process (Salomão et al. 1996). Saldarriaga et al. (1988) estimated that secondary forests on abandoned slash and burn agriculture fields would need to grow for two centuries to attain the biomass of the primary forest. Secondary forests in the Zona Bragantina region of eastern Amazonia contained less than half of the tree species of the primary forest even after 40 years of recovery (Vieira et al. 1996), while the 15-year-old secondary forest in Paragominas contained less than one third of the tree species, less than one half of the native forest ant species, and only a fifth of the forest bird species (Moutinho 1998, Nepstad et al. 1996a).

Perhaps the most important ecological affect of deforestation is that it increases the likelihood that fire will become a permanent feature of the landscape. Virtually all of the vegetation types that are planted or that regrow naturally on deforested land are far more flammable than the forests they replace (Uhl and Kauffman 1990, Cochrane and Schulze, in press). Deforestation leads to vegetation types which are easily ignited, and which can conduct accidental fires to extensive forest interfaces. Pastures, for example, can be ignited within a day of a rain event during the dry season, and logged forests can be ignited within a week or two of rainfall, while primary forests often require months without rain before they can be ignited (Fig 2.2). Decades of forest regrowth are necessary for secondary forests to recover the fire resistance of primary forests, because tall trees are needed to reestablish the full shady, moist microclimate of the primary forest interior.

Forest surface fires

The fires that ignite the organic debris lying on the ground of forests are often deceptively small, slow-moving and even innocuous in appearance (Figure 2.6). As the fire creeps along the ground at the rate of 10-30 meters every hour, a few of the insects, lizards and other fauna of the forest floor flee as the dead leaves and twigs ignite, while most are less fortunate. Plumes of smoke drift up through the forest canopy, providing the only evidence to airplane travelers above that the forest is being damaged.

The principal forest damage comes not through the destruction of the organic matter on the forest floor, nor through the mortality of the forest floor organisms that are unsuccessful in escaping the flames, although both of these effects may influence the long-term health of the forest. Rather, the most important damage caused by forest surface fire is the heating of the stems of trees and lianas beyond their tolerance limits. These limits are determined by the delicate cylinder of living cells which, through their repeated divisions, continually renew the woody water-conducting tissues of the stem core, the sugar-conducting tissue beneath the bark, and the protective bark itself. Once this cylinder of "meristem" tissue is killed through overheating, tree (or liana) death is assured during the months—or, possibly, the years—that follow (Table 3.10, Fig. 3.12).

Table 3.10. Review of literature on surface fire impacts on the structure and plant composition of tropical forests.

Fire Impacts*	Examples	Region	Reference
Tree mortality (>10 cm DBH)	70 to 90% after moderate and intense burning (excluding pioneer species)	Amazônia, Brazil	Cochrane & Schulze (in press)
	44%	Amazônia, Brazil	Holdsworth & Uhl (1997)
	36-69 %	Amazônia, Brazil	Kauffman (1991)
	96%	Amazônia, Brazil	Uhl & Buschbacher (1985)
	94%	Malasia	Woods (1989)
Juvenile tree mortality (<10 cm DBH)	73-98% after moderate and intense fire (excluding pioneer species)	Amazônia, Brazil	Cochrane & Schulze (in press)
Pioneer species density	Increase of 60%	Amazônia, Brazil	Holdsworth & Uhl (1997)
	Increase of 98% after intense fire	Amazônia, Brazil	Cochrane & Schulze (in press)
Liana mortality	> 90%	Kalimantan, Indonesia	Leighton & Wirawan (1986) *
	20-40%	Amazônia, Brazil	Holdsworth & Uhl (1997)
	20-80% after moderate and intense fire	Amazônia, Brazil	Cochrane & Schulze (in press)
Species richness**	Depends on fire intensity. May decline with intense fire because of high mortality levels, but increase with moderate fire because of increased number of gaps.		
Vegetative sprouting**	Many tree and liana species are unable to sprout following burning or excessive heating of the stem base		
Fruit Production**	Beyond outright mortality of fruit-producing trees, smoke may interfere with pollination and, therefore, fruit production. Reductions in fruit production may affect fruit-eating animals.		

*Primary forest

**Predicted.

Tree mortality and flammability: Surface fire transforms Amazonian forests by killing large numbers of trees, lianas, seedlings and herbaceous plants (Table 3.10, Fig. 3.12). As the larger trees die and decompose, they come crashing to the ground, punching new holes in the canopy and adding to the fuel on the forest floor. The single most important effect of burning is therefore the increased probability of further burning over subsequent years, as dead trees topple to the ground, disrupting the deep, moist shade of the forest interior, and building up the fuel load (Cochrane and Schulze, in press).

The amount of tree mortality caused by forest surface fire varies depending upon the amount of fuel on the forest floor, the water content of this fuel, and the microclimate of the forest interior (air temperature, humidity and wind speed) at the time of the fire. Fires ignited in forests that have little fine fuel on the ground, or that have high fuel moisture content because of a recent rain event, will burn the forest floor slowly and incompletely, leaving large patches of forest unburned. Surface fires in forests with abundant dry fuel are larger and faster, and affect much more of the forest area, killing more trees. In this context, the most flammable Amazonian forests are those that have already burned before, for these forests have abundant fuel on the ground and a leaf canopy that is interrupted by gaps created by fire-killed trees, thereby allowing a large amount of solar radiation to penetrate to the ground level and dry out the fuel layer (Cochrane and Schulze, in press). For example, fires in forests near the Tailândia frontier region of eastern Pará state, which had been moderately logged (ca. 30 m^3/ha) but not burned previously, killed approximately 40% of adult trees (trees with diameter at breast height >10 cm), representing 10% of live aboveground biomass. In the same region, fires in previously-burned, logged forests killed another 40% percent of the remaining adult trees, representing 40% of surviving above-ground biomass (Cochrane and

Schulze in press). A similarly high level of mortality (44% of adult trees) was observed in a logged forest near Paragominas that had never burned previously but was extremely dry because of the severe El Niño drought of 1992 (Holdsworth and Uhl 1997). The 1983 tropical forest fires of Borneo, Indonesia, caused adult tree mortality of 94% (Woods 1989) (Table 3.10).

Carbon emissions: Forest surface fires kill substantial amounts of forest biomass, therefore increasing the flux of carbon to the atmosphere as these dead trees decompose. This source of carbon is not included in current estimates of the carbon contribution to the atmosphere associated with human activities in Amazonia (Fearnside 1997, Houghton 1997), and would greatly increase these estimates if it were included. For example, if we assume that in an average year approximately 10,000 km^2 of forests experience surface fire (less than the area estimated in Section 3.5) that kills 25% of above-ground biomass (that is, a level of mortality intermediate to the measurements made in Pará), and if we assume that the average carbon content of these forests is 200 tons per ha (post-logging value derived by Fearnside 1997), then surface fires would be responsible for the annual release of ~50 million tons of carbon to the atmosphere. This represents a 20 percent increase in carbon emissions from Brazilian Amazonia over current estimates (Fearnside 1997). If a severe El Niño drought led to the burning of 100,000 km^2—which is half of the forest area that we predicted were highly susceptible to fire in 1998 (Chapter 4)—the carbon flux associated with forest surface fire would be 500 million tons, nearly tripling the current estimates of carbon emissions from the region and pushing to approximately 11% the Amazon contribution to the global release of carbon to the atmosphere from fossil fuel combustion and deforestation each year (Fearnside 1997, Houghton 1997). Such a cataclysmic Amazon fire episode would increase carbon emissions in subsequent years as well, as the highly-flammable burned forests experienced recurrent fires, releasing more of their carbon into the atmosphere.

Forest structure: Beyond its effects on forest flammability and carbon content, surface fire dramatically changes the structure of Amazon forests (Fig. 3.13). The fire kills virtually all of the seedlings, sprouts, lianas and young trees that it encounters, for these small plants are not protected from fire by thick bark as are many large trees. By reducing canopy leaf cover the fire also favors the establishment of water-, light- and nutrient-demanding pioneer trees, such as members of the genus *Cecropia*, *Vismia*, and *Solanum* (Cochrane and Schulze, in press; Holdsworth and Uhl 1997). Lianas appear to be particularly susceptible to mortality by fire (Table 3.10).

Forest fauna: The effects of surface fire on Amazonian forest fauna are potentially large, but have not been studied. Populations of forest turtles and other slow-moving animals, including much of the litter fauna, are certainly severely reduced by fire. The death of fruit trees provoked by fire may lead to food shortages for frugivorous forest mammals, in a similar way as severe drought leads to food shortages and population reductions in tropical forest mammals. The species of Amazon forest mammals that depend upon fruit for their diet, and that may suffer population reductions as a result of forest fire, include tapir, large monkeys, wild pigs, deer, and agoutis. Indeed, hunters interviewed near Paragominas report lower hunting success in forests following surface fire (M. Mattos, K. Carvalheiro, D. Nepstad, unpublished data).

In Australia, forest fire drastically reduced small mammal populations, perhaps because these creatures respond to fire by seeking shelter in hol-

Fig. 3.13. A forest three years after experiencing a surface fire, in the Del Rey farm community. Forest surface fire kills trees with thin bark, and opens the canopy, permitting the establishment of pioneer trees such as Cecropia *spp. and* Solanum *spp. (Photograph by D. Nepstad)*

low trees and other flammable structures (Friend 1993). The same study found relatively low fire impacts on reptile and amphibian populations.

Hydrology: Surface fire may also alter the water cycle of Amazon forests in two important ways. First, tree mortality leads to a reduction in leaf area, which decreases the amount of water that is leaving the forest through transpiration. Amazonian forests transpire so much water that they play an important role in the regional climate system (Salati and Vose, 1984). The water molecule that evaporates from a leaf at the top of a forest canopy in Paragominas may condense as part of a rain drop falling from a cumulus cloud that forms over Altamira, 300 km downwind. This tight linkage between the evaporation of water from forest leaves and other surfaces (called "evapotranspiration") and rainfall patterns has been demonstrated in several climate models developed for this region (Lean and Warrilow 1989, Nobre et al. 1991, Shukla et al. 1990, Victoria et al. 1991).

The reduction in leaf area that results from forest surface fires also reduces the amount of rain that is retained by the canopy, because there is less surface area for water to adhere to. Hence, surface fires increase the amount of water that enters the soil when it rains. The combination of these two effects—decreased evapotranspiration and increased throughfall of rain down to the soil—causes an increase in soil moisture, and, therefore, an increase in the amount of water that seeps down into the water table. Since it is the water table that feeds the streams and rivers of the region, forest surface fires increase stream and river flow, with an unknown impact on the communities of fish and other aquatic animals. These effects on the water cycle are reversed, however, when leaf area is reestablished in the forest through the growth of new trees and lianas, or through the branching of trees and lianas that survived the fire. The rate of forest recovery of leaf area following surface fires has not been studied.

Fires on deforested land

Pastures: Unlike the apparently innocuous fires of the forest understory, Amazonian pasture fires are often higher than 5 meters, and they can move rapidly across the landscape when driven by the wind. When these fires blaze across pasturelands, they convert most of the aboveground biomass of the vegetation into gases (carbon dioxide and monoxide, nitric and nitrous oxides, sulfur oxide), airborne particulates (i.e., smoke), and ash. Virtually all of the living above-ground biomass is killed, and its carbon released to the atmosphere as carbon dioxide; large amounts of important plant nutrients (e.g., 50% of phosphorus stocks in biomass, Kauffman et al. 1998) are also sent skyward. Some of the nutrients contained in the vegetation are deposited on the soil as ash, which can stimulate plant growth during the subsequent rainy season, and which is one of the reasons that landholders deliberately set their pastures on fire to stimulate forage grass production. Some of this ash is blown or washed away, however, and is therefore lost to the pasture ecosystem. One of the most important effects of burning on pastures is the loss of mineral nutrients to the atmosphere and to streams, for this loss could mean reduced productivity in the future if nutrient shortages limit plant growth (Dias Filho et al., in press).

The smoke produced by pasture fires causes air pollution. During the burning season of 1997, the air quality in some places of rural Amazonia was worse than that of São Paulo's inner city, largely because of the smoke produced by fires on deforested land.[5] Moreover, the loss of nutrients to streams may provoke eutrophication (nutrient-stimulated biological activity) and undesirable build up of algae.

Pasture burning also influences the plant composition of the pasture, favoring grasses over woody plants. The meristem of grasses, responsible for the growth of new leaves, are at or below the ground surface, protected from the fire, while similar tissues of woody plant stems are just under the bark and are more easily killed by fire. Burning stimulates the rapid growth of grass leaves, while it kills the aboveground tissues of woody plants. Some of these woody plants resprout from the roots or stem base following burning (e.g. *Solanum crinitum, Vismia guianensis* and *Stryphnodendron pulcherimum*, Nepstad et al. 1996). Hence, one of the most important impacts of fire on pasture is to set back

[5] Paulo Artaxo Neto, personal communication.

plant succession by killing the aboveground parts of those woody plants. In the event that a pasture is abandoned, these woody invaders of the pasture play an important role in facilitating tree establishment by attracting tree seed dispersal agents and by providing microclimatic and edaphic conditions that are more amenable to tree growth (Nepstad et al. 1991, 1996b, Vieira et al. 1996)

Unlike forest fires, burning decreases the flammability of the pasture by consuming virtually all of the fine fuels. Grass leaves accumulate from one year to the next until they reach an equilibrium in which the rate of new grass production is equal to the rate of dead organic matter decomposition. The effect of fire on pasture flammability is much less pronounced where cattle grazing reduces the amount of grass and other fine fuel.

Despite the very large area of pasture that is burned each year relative to deforestation and forest surface fire (Fig. 3.8), this type of burning contributes very little to the carbon emissions associated with Amazon land uses. The carbon stocks of pastures (ca. 3 to 7 tons/hectare) are low compared to the carbon stocks of forests (ca. 200 tons per hectare), and are quickly restored after the fire. That is, the carbon released to the atmosphere through pasture burning is compensated within a year or two as the pasture vegetation regrows, removing a similar amount of carbon from the atmosphere.

Secondary forests: Fires that burn secondary forests kill most of the aboveground tissues, releasing smoke and gases to the atmosphere and setting back the process of forest recovery (Nepstad et al. 1995). Since the trees of secondary forests are small in stature and generally require many years to develop bark sufficiently thick to protect against fire damage, the mortality of stems is high. However, many species of secondary forests are able to sprout following burning; roughly two thirds of the tree species of a secondary forest near Paragominas sprouted following a fire (Kauffman 1991).

Fires in secondary forests release more carbon to the atmosphere than fires in pastures. As forests regrow on abandoned land, they accumulate 1 to 5 tons of carbon per year in aboveground biomass; hence, fires that kill all of the aboveground tissues of young (5-year-old) secondary forests release approximately 5 to 25 tons of carbon to the atmosphere (Salomão et al. 1996). Fires in secondary forests also set back the recovery of hydrological processes, such as evapotranspiration (Jipp et al. 1998).

Fire and the savannization of Amazonia: a vicious positive feedback loop?

The biggest ecological impact of Amazonian fire could be the replacement of vast areas of closed-canopy evergreen forest with savanna-like, fire-prone scrub vegetation through the synergistic effects of increasing drought and human land-use activities. In this scenario—which is, unfortunately, quite plausible—forests that become susceptible to fire because of the effects of either severe seasonal drought, logging activities, or both (Chapter 2) are ignited by agricultural fires that escape their intended boundaries and, once burned, become even more vulnerable to subsequent burning. Forests that experience recurrent fires become depleted in trees, and the perforated leaf canopy allows sufficient sunlight to reach the forest floor for grasses to invade, greatly increasing the amount of fine fuel near the forest floor and preventing the establishment and growth of tree seedlings. What was once a dense evergreen forest with deep shade becomes an impoverished forest populated by a few fire-resistant tree species and a ground cover of weedy grasses, forbs and shrubs (Cochrane and Schultze in press, Nepstad et al. 1995). The process of savannization could be reinforced, or accelerated, if the replacement of dense forest with impoverished, fire-prone vegetation decreases evapotranspiration and energy absorption sufficiently to provoke regional reductions in rainfall, as is predicted by current climate models (Lean and Warrilow 1989, Nobre et al. 1991, Shukla et al. 1990) (Fig. 3.14). Large-scale savannization in Amazonia is the most worrisome ecological outcome of current patterns of fire use in the region because it represents a semi-permanent replacement of species-rich forest by an impoverished vegetation which is depauperate in native plant and animal species, much reduced in biomass, and less capable than the native forest of maintaining regional precipitation patterns through evapotranspiration.

3.7 Economic effects of fire

Costs to landholders

Fires affect the water, carbon and nutrient cycles of Amazonian forests, they deplete populations of wildlife, and they damage the forest's capacity to act as a natural firebreak in the landscape. But many of these ecological costs of fire have little or no perceivable value to the Amazonian farmer or rancher whose forests burn, because they do not translate into changes in their economic well-being. Similarly, when farmers set fires to clear or prepare their land, they may fail to account for the risk of fire spreading to their neighbors' land, due to ineffective enforcement of laws requiring compensation for damages imposed on others. In this section we discuss the direct costs of fire to Amazonian landholders, including the damages to their production systems that are inflicted by fire, and the investments that they make in pre-

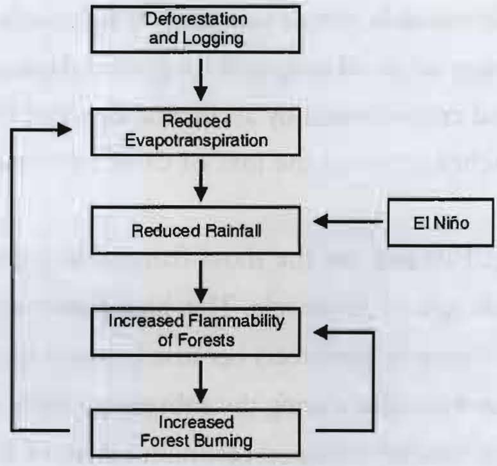

Fig. 3.14. Forest surface fires may provoke a vicious cycle of forest impoverishment, in which burning contributes to a decrease in rainfall and an increase in forest susceptibility to fire, both of which increase the likelihood of further burning. The interaction of drought and fire could lead to the large-scale replacement of closed-canopy forest with grass-dominated, fire prone vegetation, extending the range of the Brazilian Cerrado further into the Amazon. Adapted from Nepstad et al. 1995 and Cochrane and Schulze, in press.

venting accidental fire. There are only two fire damages for which we were able to obtain data through our property-level study, both involving pasture: damage to fences and loss of forage. We also obtained data for one of the costs of preventing accidental fire: the preparation of firebreaks. We present these damages and costs for the four size-classes of properties that we studied, and conclude this section with a discussion of the likely magnitudes of other economic costs of fire that we were unable to quantify.

In the five regions studied, 90% of the property owners reported economic losses through accidental burning of their pasture forage. One third of the owners interviewed reported fence damages caused by accidental pasture fire, and one fourth of the owners reported losses of commercially valuable timber caused by forest surface fires. Nearly half of the owners of small properties reported damages to their annual or perennial crops caused by accidental fire, and 8% of the owners of large ranches reported the loss of cattle or horses to fire.

Forage damage: Pastures are the most flammable component of the agricultural landscape of Amazonia. This high flammability is a source of much worry for cattle producers because pastures that burn must be "rested" for 3 to 4 months during the subsequent rainy season to reestablish leaf cover. One of the biggest economic costs of fire in Amazonia is the loss of forage during the dry season. When pastures burn, land owners must find a replacement pasture to maintain their cattle herds, which often means renting pasture from other landholders.

To estimate the cost of accidental pasture fires to Amazonian landholders, we first multiplied the cost of renting pasture ($3 to $3.6/hectare/month) by the average number of months that is needed for burned pastures to recuperate sufficiently to support cattle again (3 to 4.5 months), then multiplied this value by the average numbers of hectares of pasture that burned per property (Table 3.11). These calculations show that the annual costs associated with accidental burning that arise from lost grazing are, on average, $20, $180, $1,150, and $8,110 for small, medium, large and very large properties, respectively (Table 3.11)

Fence damage: Fences in Amazonia are usually made of wooden posts spaced at 2 to 3 meter intervals that support three to four strands of smooth or barbed wire. When a fence burns, the damage can vary from complete destruction of the fence to the heating of the wire, which exposes the wire to rapid deterioration through rusting. When we add together the costs associated with fence replacement reported

Table 3.11. Pasture area, range of annual profits, area of pasture accidentally burned each year, and the damages caused by this burning to fencing and grazing.

Property Area (ha)	Pasture Area (ha) mean ± SE	Annual Profit (US$)[1] Minimum	Annual Profit (US$)[1] Maximum	Accidentally Burned Pasture (ha)[2]
Small (0-100)	31 ± 3	153	1,529	2
Medium (101-1000)	247 ± 26	1,235	112,354	20
Large (1001-5000)	1,048 ± 84	5,242	52,425	128
Very Large (>5000)	8,292 ± 2,481	41,462	414,623	901

Fire Damages (US$)[3] Fencing (wire only)	Fire Damages (US$)[3] Fencing (wire & posts)	Fire Damages (US$)[3] Grazing	Fire Damages (% of Profit)[4] Fencing	Fire Damages (% of Profit)[4] Grazing	Fire Damages (% of Profit)[4] Total
27	134	21	2 to 88%	1 to 14%	3 to 102%
114	564	183	1 to 46%	1 to 15%	2 to 61%
213	1,053	1,150	0 to 20%	2 to 22%	2 to 42%
3,387	16,710	8,112	1 to 40%	2 to 20%	3 to 60%

1. Minimum profit assumes a net profit of $5/yr/ha and maximum assumes a net profit of $50/yr/ha (Mattos and Uhl 1994).
2. Average area accidentally burned, from property-level interviews.
3. Fire damages. Fencing: length of damaged fence x price of wire ($300/km), and length of damaged fence x price of complete replacement (wire and posts) ($1400/km). Grazing: number of burned hectares x 3 months of pasture recuperation x $3/mo. (pasture rental). All data from property-level interviews.
4. Fire damages as percent of profit: Fencing damage ranges from a low value, which assumes that only wire is damaged and maximum pasture profits, to the high value, which assumes complete fence destruction and minimum pasture profits. The range of grazing values was determined using two levels of profitability (1).

by landholders, including labor, posts, wire, and transport of the posts and wire, we find that the average cost of replacing a fence entirely is $1,400 per kilometer, while the cost of replacing the wire on a fence is $300 per kilometer. These values, multiplied by the average length of fence lost to fire as reported by landholders indicate that, depending on the size of their holding, farmers and ranchers lose $27, $114, $213, and $3,387 worth of fence wire alone through damage from accidental fire (Table 3.11).

To place the costs of accidental pasture fires into the perspective of the landholder, we compared them to the profits derived from cattle production. The range of possible net profits was calculated by multiplying the average area of pasture within each property size class by the average profits of both extensive ($5/ha/yr.) and semi-intensive ($50/ha/yr.) forms of pasture production (Mattos and Uhl 1994). The costs of accidental burning range from a low of 2 to 3%, assuming semi-intensive pasture management and fence losses associated only with wire damage, to >100% of annual profits, assuming that pastures are managed extensively and that burned fences must be completely replaced (Table 3.11).

Losses associated with accidental pasture burning are not incurred by individual landholders at the average rate each year. Rather, accidental fires are episodic, with a large degree of variability in the areal extent of burning where it does occur. Accidental fire in pastures is a risk that varies from year to year depending upon rainfall patterns and can be reduced through investments in fire prevention techniques.

Firebreaks are the most expensive, but most important, technique available to rural Amazonian producers to prevent the escape of their intentional burns, and to protect their fields and forests from the incursion of fires that escape from neighboring properties (see Section 5.2). They are strips of land that are 2 to 5 meters wide from which most flammable material has been removed manually using machetes, or mechanically using bulldozers. These strips can be much narrower in forests, where 0.5 m is often sufficient to prevent the passage of the slow-burning fires that burn in the forest understory (Fig. 2.6).

Virtually all (98%) of the property holders that we interviewed reported that they employed firebreaks to contain their fires or protect their fields and forests. Most property holders (93%) used firebreaks to protect their pastures from accidental burning while only 40% used firebreaks to protect their forests. More than half of the holders of small properties used firebreaks to protect their crop fields vs. only 20% of the medium and large property owners. Most of the property owners interviewed (72%) made firebreaks somewhere on their property every year.

Firebreaks can be made much more cheaply with bulldozers ($20 per km) than with machetes ($60 per km), and therefore are more expensive for the holders of small properties, who have little access to heavy machinery. Nearly all (90%) of the holders of small properties who made firebreaks did so manually, while 61% and 22% of medium and large property holders used this technique. This trend was reversed for the use of bulldozers: 2, 30, and 50% of the holders of small, medium and large properties employed bulldozers to make their firebreaks.

The average annual investment by landholders in firebreak preparation for the protection of pastures and crop fields can be calculated by multiplying the average cost of preparing the firebreak by the average length that is prepared. Each year, the property holders interviewed spend an average of $94, $194, $518, and $6,840[6] on small, medium, large and very large properties, respectively, in firebreak. This investment represents approximately 61, 16, 10 and 16% of annual profits from cattle production assuming extensive pasture management, and only 1 to 6% of annual profits assuming semi-intensive pasture management (Table 3.12).

Another way of illustrating the very high relative costs of investments in manual fire prevention for areas of low productivity is to calculate the percentage of profits from cattle production that would be needed to circumscribe a 100-hectare pasture with a firebreak assuming two levels of cattle pasture management and two techniques for making the firebreak. Nearly half of the profits stemming from 100 hectares of unproductive pasture would be needed to make a manual firebreak, while only 2% of the profits of a productive pasture are necessary to make a mechanized firebreak (Table 3.13).

Forest losses: Accidental fires may burn a 13,000 to 25,000 km^2 or more of standing forest each year, destroying timber and killing plants that are sources of fruits, medicines, building materials, and that hold spiritual or ceremonial value. The losses of timber to forest surface fire are diminished by the fact that most of the forests that burn have

[6] These figures were calculated assuming that the length of firebreak prepared using each of the two methods (manual vs. bulldozer) is proportional to the method that was cited by property owners as their principal method of preparing firebreaks.

Table 3.12. Pasture area, range of annual profits from cattle production, and estimate of percentage of these profits devoted to fire break preparation.

	Pasture Area (ha)	1 Annual Profit (US$/yr)		2 Cost of Firebreaks	3 Investment in Fire Breaks	
Property Size (ha)	mean ± SE	Minimum	Maximum	(US$)	% of Min. Prof.	% of Max. Prof.
Small (0-100)	31 ± 3	$153	$1,529	$94	61%	6%
Medium (101-1000)	247 ± 26	$1,235	$112,354	$194	16%	2%
Large (1001-5000)	1048 ± 84	$5,242	$52,425	$518	10%	1%
Very Large (>5000)	8292 ± 2481	$41,462	$414,623	$6,840	16%	2%

1. Calculated by multiplying the pasture area by profits ($/ha/yr.) of extensive (minimum) and semi-intensive (maximum) cattle pasture production systems, following Mattos and Uhl (1994).
2. Calculated by multiplying the average length of fire break constructed per year that landholders in each property size class reported by the cost per kilometer of firebreak.

   The portion of firebreak constructed using machetes and ractors was determined from the interviews and used to weight the calculation of the cost of the firebreaks. A kilometer of fire break costs $60 using machete and $20 using tractor, based on the landholder interviews.
3. Calculated as the cost of fire breaks (2) divided by the minimum and maximum net profit (1).

Table 3.13. The relative costs of fire breaks to circumscribe a 100-hectare (1 x 1 km) pasture using two types of cattle pasture management, and two techniques for making fire breaks.

	Profit (US$/yr)	Cost of Fire Break (% of Net Profit) Manual	Tractor
Extensive pasture	500	48.0	16.0
Semi-Intensive pasture	5000	4.8	1.6

1. Profits calculated from Mattos and Uhl 1994.
2. Fire break costs calculated from Table 3.12.

already been logged. But even logged forests have residual timber trees that can be lost to fire (Holdsworth and Uhl 1997). A surface fire in a logged forest near Paragominas, for example, destroyed $5 worth of timber per hectare, and therefore cost the landholder approximately $500.[7] These timber losses can be much higher when fire burns forests that have not been logged. The value to sawmill operators of the standing timber in their unlogged forests can be as high as $200 per hectare. Total timber losses to Amazonian landholders resulting from surface fire are likely to exceed several million dollars per year, and may reach tens of millions of dollars if large areas of unlogged forests catch fire because of drought-induced fire susceptibility (Chapter 4).

The economic losses associated with forest fire may be much more significant for small holders who depend upon the forest for a wide range of subsistence uses than for large landholders, who use forests primarily for timber. In communities of farmers along the Capim River, near Paragominas, households consume 8 kilograms of wild meat each month, which provides one fourth of the recommended minimum daily protein consumption (Cymerys et al. 1997). Subsistence hunters in the nearby community of Del Rey reported lower hunting success in forests that had burned recently compared to forests that had not burned.[8] Fires in this region destroy lianas that are important sources of building material (e.g. "cipo titica", *Heterolepsis;* "cebolão", *Clusia grandiflora*), fruit trees such bacurí (*Platonia insignis*), piquiá (*Caryocar villosum*) and "uxí" (*Endopleura uchi*), and numerous medicinal plants.

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[7] A. Holdsworth, unpublished data on stumpage value of killed trees.

[8] M. Mattos, D. Nepstad, unpublished data.

Forest surface fires also make slash and burn agriculture more dangerous for smallholders because of the increased risk that branches will fall on them when they cut patches of forest down. Trees killed by surface fire begin to rot while they are still standing, and pose a risk to the people who are felling the forest.[9]

Orchards and plantations: Orchards of fruit trees such as oranges (*Citrus*), Barbados cherry (*Malpighia punicifolia*), "cupuaçu" (*Theobroma grandiflora*), cocoa (*Theobroma cacau*), coffee (*Coffea robusta*) and cashew (*Anacardium occidentalis*); plantations of passion fruit (*Passiflora edulis*), black pepper (*Piper nigrum*), oil palm (*Elaeis guineensis)*, veneer species (e.g. "paricá", *Schizolobium amazonicum* and teak, *Tectona grandis,* Figure 3.6), pulp species (e.g. eucalyptus, *Eucalyptus deglupta*, and Caribbean pine, *Pinus caribea*), and timber species (e.g. mahogany *Swietenia macrophylla*) are all highly susceptible to accidental fire. Accidental fires in these plantations probably cause a higher per-hectare economic cost than any type of accidental fires in Amazonia because of the large financial investments that are needed to establish these perennial crops. The economic value of this type of accidental fire has not been documented.

Costs to society

Fires erode the capacity of Amazonian ecosystems to support life and thereby affect all human society. In 1997, the costs of forest fires in Indonesia associated with timber destruction, oil palm plantation damage, and haze totaled $4.4 billion.[10] A similar evaluation has not yet been conducted for Amazonia. Many of the costs of fires to society

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[9] M. Mattos, K. Carvalheiro, D. Nepstad, unpublished data.

[10] Economic and Environment Program for South East Asia 1998

are difficult to quantify in monetary terms because they involve ecological processes and services that are not traded in the marketplace, but that sustain the production of food, fiber, and other commercial products. These ecological services include the role of forests in maintaining the Amazonian water cycle and the regional climatic system, as described in Section 3.6, above. Amazonian forests protect soils from the erosive force of rain and wind, and contribute organic matter to these soils that maintains their structure and fertility. They are a repository for the greatest library of genetic information in the world, information that is the source of organisms and substances that are needed to combat disease and provide food for an expanding human population. Amazonian forests act as natural firebreaks across the landscape, preventing the spread of fires that escape from agriculture.

Smoke: One of the most visible costs to society of Amazonian fire is associated with the smoke released by burning. The residents of rural Amazonia breathe air that is more polluted than the air in downtown São Paulo for weeks on end.[11] The smoke invades urban centers, sending tens of thousands of Amazonian city-dwellers to health clinics with bronchitis, asthma and other respiratory ailments. According to the Brazilian Ministry of Health, twice as many patients are admitted to hospitals each month because of respiratory ailments during the peak of the burning season than during other months of the year. Smoke reduces visibility, provoking traffic accidents, and causing airport shutdowns in Amazonian cities. In 1996 and 1997, the airports in Rio Branco (Acre), Porto Velho (Rondônia), Imperatriz (Maranhão), and Conceição de Araguaia, Carajás, and Marabá (Pará) were forced to close for a total of 420 hours because of smoke.

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[11] Paulo Artaxo Neto, personal communication.

Fire damages to rural electric lines interrupts energy transmission. In 1995, forty-seven fire-induced interruptions of energy transmission from the Tucuruí hydroelectric reservoir cost the energy company (ELETRONORTE) approximately US$2.2 million in profits.[12] This cost does not include the costs to businesses and households that purchased generators, and suffered food spoilage and sleep loss because of interruptions in energy.

A thorough assessment of the economic impacts of Amazonian fires is a very high research priority, for a quantification of these impacts may be the most effective way of communicating to decision-makers the importance of finding solutions to the Amazon fire problem.

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[12] Eletronorte – Internal Report

4. Future Burning

The problem of accidental fires in Amazonia may become worse in the coming years. El Niño events are associated with severe droughts across much of Amazonia, and have become more frequent in the last 15 years. One group of climatologists recently concluded that this increase in El Niño events is associated with the accumulation of carbon dioxide in the atmosphere (Trenberth and Hoar 1997), and could therefore represent the beginning of a long-term trend. Rainfall reductions in Amazonia are also a predicted outcome of Amazonian deforestation itself (Nobre et al. 1991, Shukla et al. 1990). Either of these trends would exacerbate the problem of Amazonian fires by increasing the susceptibility of forests, pastures and plantations to conflagrations.

Accidental fires may also increase in the coming years because of the expanding agricultural and timber frontier. As roads such as the Santarem-Cuiabá, the Manaus-Boa Vista, and the Acre-Pacific are paved, a chain reaction of logging, colonization by landless poor, and large-scale forest conversion to cattle pasture by large landholders will both increase the flammability of vast stretches of new forest, and introduce fire sources through traditional agricultural and pasture management practices. There is no evidence that we are aware of that would suggest a slowing of frontier expansion in Amazonia, or widespread adoption of more intensive, less fire-prone land-use practices.

The prediction of future fire scenarios for Amazonia—and the influence of public policy change on these scenarios—is a crucial task for science. In this chapter, we describe a model that incorporates a wide variety of data to predict future Amazonian fire regimes. Further development of this model could provide a powerful tool for illustrating to Brazilian society the impacts of current rural development trends in Amazonia, and for helping producers plan this fire prevention investment.

A Fire Prediction Model

Over the last three years, IPAM and WHRC have been developing a model, called "RisQue" (from the Portuguese, "Risco de Queimadas e Incêndios") to identify regions of fire risk for the Brazilian Amazon. This model integrates data on rainfall, soils, forests, logging, agriculture and the history of fire occurrence to generate maps of forest susceptibility to fire, and the probability that agricultural lands will catch fire and ignite these forests (Fig. 4.1). Fire risk prediction is a formidable task in Amazonia because of the region's tremendous size, its broad diversity of forest and soil types, and the wide range of land-use practices that are employed along the agricultural frontier. However, knowledge of the factors that lead to forest flammability (Chapter 2), studies of the characteristics of rural properties that are associated with the use of fire and fire prevention effort, rainfall and temperature data from across the region, and satellite based measurements of active fires (Section 3.1) provide the basis for a fire prediction model, as we describe here.

<u>The flammability of intact forests:</u> We begin with the task of predicting the rainfall regime under which mature, intact forests (that have not been logged) become susceptible to fire. Field studies (Chapter 2, Nepstad et al. 1994, 1995, Kauffman et al 1988) have demonstrated that the closed-canopy forests of Amazonia can maintain dense leaf canopies—and, therefore, shady moist microclimates in the forest interior—during dry periods lasting 5 to 6 months by absorbing water

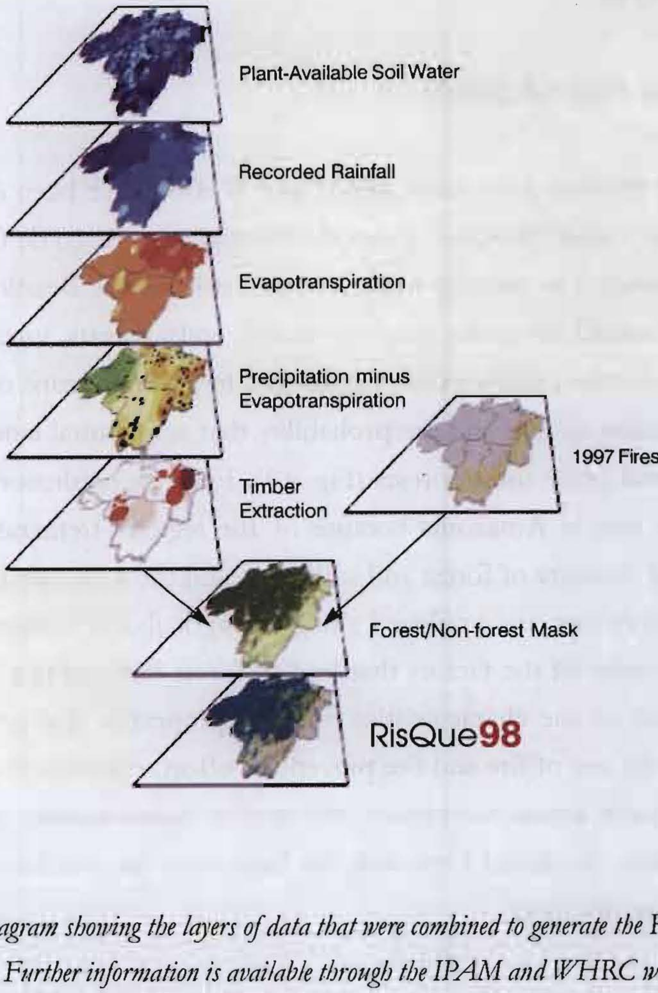

Figure 4.1 Diagram showing the layers of data that were combined to generate the RisQue fire risk maps. Further information is available through the IPAM and WHRC websites: http://www.ipam.org.br and http://www.whrc.org.

stored in the soil to depths of more than five meters, thereby avoiding drought-induced leaf-shedding. Because of this remarkable adaptation to seasonal drought, Amazon forests become vulnerable to fire only after prolonged periods during which the amount of rainfall coming into the forest is less than the amount of water leaving the forest via evapotranspiration. Prediction of forest susceptibility to fire can therefore be viewed as the process of estimating the rainfall regime at which soil water uptake to supply evapotranspiration depletes so much of the water stored in the soil that severe drought stress provokes leaf-shedding and the forest floor becomes vulnerable to fire.

A soil moisture component of our model incorporates this knowledge of drought effects on Amazon forest flammability to provide monthly, Amazon-wide maps of those forests that are vulnerable to fire because of drought. This component treats the soil of Amazon forests as a sponge which is filled up with water by incoming rainfall, and dried out as the forest extracts water from the soil to supply evapotranspiration. As the sponge is dried out by the forest, a level is reached below which forests become flammable; this "flammability threshold" level of soil moisture is determined through field measurements in five Amazonian forest types.

The amount of water that the soil "sponge" can hold determines the number of days without rain that forests can continue to release water vapor into the atmosphere through evapotranspiration before drought stress begins to trigger leaf-shedding. Forests with big sponges can avoid drought-induced leaf-shedding and vulnerability to fire for longer rainless periods than forests with small sponges. We calculate the sponge size for each soil type as the difference between the amount of water stored in the soil when it is fully charged with water (called "field capacity") minus the amount of water that is stored in the soil at such high tensions that plants simply cannot extract it (called the "permanent wilting point" of the soil). We have calculated the "sponge size" for the soils of Amazonia (Negreiros et al. 1998, Potter et al. 1998, Nepstad et al. 1998b) using soil texture data from 1142 soil profiles and empirical equations that relate soil texture to water retention properties of the soil (Saxton et al. 1986, Tomasella and Hodnett 1998). When the soil is fully charged with water following prolonged periods of heavy rain, most of the forests of Amazonia can continue to release water vapor into the atmosphere through evapotranspiration for several months without receiving additional rainfall.

In the model, forests remain resistant to fire until evapotranspiration dries out the soil sponge. At this "flammability threshold", drought has provoked sufficient leaf-shedding that the fine fuel layer of the forest floor can be ignited following short periods without rain. The flammability threshold can be determined for a particular forest type by igniting experimental, controlled fires on the forest floor under a range of soil water contents (and a corresponding range of leaf area indices). We define the flammability threshold as the leaf area index below which experimental fires do not go out on their own, but begin to spread, within 10 days of the last fuel-penetrating rain event. We are measuring the flammability threshold in five forest types, including (1) dense evergreen forests ("floresta densa ombrofila") in Paragominas and the Tapajós National Forest, (2) liana forests ("floresta cipoôlica") in the same sites, (3) open forests ("floresta aberta") in the Catuaba Reserve of Acre, (4) bamboo forests ("floresta de bambu"), also of Catuaba, and (5) transition forests ("floresta de transição"), near Santana do Araguaia (Fig. 1.1).

Other measurements are also made at each of these sites to facilitate the prediction of forest flammability. We measure fuel characteristics (height, size class distribution, moisture content, mass), air temperature and relative humidity, and, in clearings located close to the forest study site, we measure solar radiation, air temperature, air relative humidity and windspeed.

Logging. Selective logging causes standing forests to become vulnerable to fire by opening up the leaf canopy and by increasing the amount of fuel on the forest floor (Uhl and Kauffman 1990). The RisQue model incorporates the effects of selective logging on forest vulnerability to fire by increasing vulnerability where logging is taking place, weighted according to the intensity of logging. The effects of logging on forest vulnerability to fire is directly related to the volume of wood that is harvested from the forest: high harvest intensities have a greater influence on forest susceptibility to fire than do low harvest intensities.

Deforested land: RisQue also calculates the probability that land that is already deforested will catch fire. This prediction serves two important functions. First, it provides fire risk information to the residents of rural Amazonia to help them decide how much to invest in fire prevention and control to protect agricultural production systems and infrastructure on deforested land. Second, it provides information on the probability that forests vulnerable to fire will be ignited.

Fire risk prediction on non-forest land requires a different approach than the one developed to predict forest fire risk. The flammability of pastures, plantations, secondary forests and annual crop fields is much greater than the flammability of intact forests (Uhl and Kauffman 1990), and fire risk is largely a function of the ways in which landholders use fire on their land, their investments in prevention of accidental fire, and the short-term rainfall history. We hypothesize that fire risk is inversely related to the level of investment that has been made in rural properties. In other words, we predict that investments in fire-vulnerable improvements to the land, such as fencing, agroforestry systems, tree plantations and other perennial crop production systems, pasture reform, and buildings, act as a disincentive for landholders to burn and as an incentive for landholders to invest in fire prevention and control. Moreover, other factors, such as distance to market and land tenure security, and absenteeism, may be determinants of fire risk. We are currently testing this hypothesis through property-level interviews and analyses of satellite images, in which we compare the level of investment made in rural properties with the history of fire occurrence on that property. Our hope is that we will identify robust indicators of landholders' propensity to utilize fire as a management tool, and to invest in the prevention and control of accidental fire, such as the amount of fertilizer used, the number of bulldozer-hours used in land management, and the production of tree crops. Once identified, such indicators could allow us to employ data from the Brazilian federal agricultural census, and other frequent surveys, to estimate the level of fire risk in the municipalities (*municípios*) of Brazilian Amazonia. Fire risk would be adjusted up or down as a function of recent rainfall history.

While we develop this economic model of fire prediction on deforested lands together with the International Institute of Environment and Development (IIED), we are also testing the hot pixel data available from the NOAA AVHRR sensors (Section 3.1) as an indicator of those deforested lands that are most likely to catch fire. High concentrations of hot pixels indicate a large amount of land management activity, which may continue from one year to the next. When high concentrations of pixels are located close to forests that we predict are vulnerable to fire, the risk of forest fire rises accordingly. However, very high concentrations of hot pixels may be associated with fires that are so extensive that they consume most of the available fuels, and are associated with a lower probability of fire during the subsequent year. The hot pixel data will become more useful now, with the installation of new receiving antennas in Cuiabá and Lima, Peru, and as another antenna is installed in Belém. These antennas will provide complete coverage of Amazonia, and a redundancy of measurements should prevent the loss of hot pixel data when a receiving station malfunctions.

RisQue98: The fire risk map of 1998

The powerful El Niño event of 1997 and 1998 provoked severe drought in Amazonia during the 1997 dry season, and below-average rainfall during the subsequent rainy season. This rainfall reduction desiccated the soils of large areas of Amazonian forest, creating the potential for enormous losses through accidental forest fires during the 1998 dry season. IPAM warned Brazilian officials of this fire threat in a public hearing held in the Brazilian National Congress in March, 1998. One of the government's responses to this warning was to request IPAM's assistance in identifying those regions in Amazonia where the threat was most severe. To attend to this urgent need, IPAM, WHRC, IMAZON, INPE, and NASA-Ames developed a preliminary version of the RisQue model to identify those forest areas that would be most vulnerable to fire during the 1998 dry season, and those areas of deforested land where fires were most likely to occur. "RisQue98" was developed using the procedures described for RisQue above (Fig 4.1, Nepstad et al. 1998b), but relied on NOAA/AVHRR hot pixel data from 1997 as an indicator of those deforested lands most likely to be ignited in 1998, and rainfall data from INPE/CPTEC through May, 1998. IMAZON provided data on those Amazonian forests that were subjected timber harvesting, and NASA-Ames calculated the water-holding capacities of Amazonian soils using new equations derived by Tomasella and Hodnett (1998).

RisQue98 predicts that approximately 207,000 km^2 of forest were at "very high" risk of becoming vulnerable to fire late in the 1998 dry season (November), that is, these forests would fully deplete the plant-available water stored in the soil to a depth of 5 meters by this time (Figure 4.2). The largest areas of fire-vulnerable forest, in eastern and southern Pará state, were also regions of high densities of fires detected by the NOAA satellite in 1997, and therefore had a large chance of being ignited by escaped agricultural fires (Figure 4.2). The total area of forest at risk of catching fire in 1998 was estimated at 400,000 km^2 for November when areas of forest with less than 300 mm of plant-available moisture in the upper 5 meters of soil were added to the areas of very high risk (Figure 4.2).

As this book went to press, fires were burning the forests of Tocantins and northern Mato Grosso (Ilha Bananal), Redenção (southern Pará), and Marabá[13] (D. Nepstad, unpublished data), located in areas classified as "very high risk". However, fires were also threatening the forests of eastern Acre, where low forest fire risk was predicted. This discrepancy arises because the predictions set forth in RisQue98 are based on the assumption that rainfall from May to November was equal to the average rainfall of previous years.[14] In fact, rainfall during this period was below average in Acre and in portions of Mato Grosso and southern Pará. Hence, RisQue98 underestimates the areal extent of fire-vulnerable forest in the 1998 dry season.

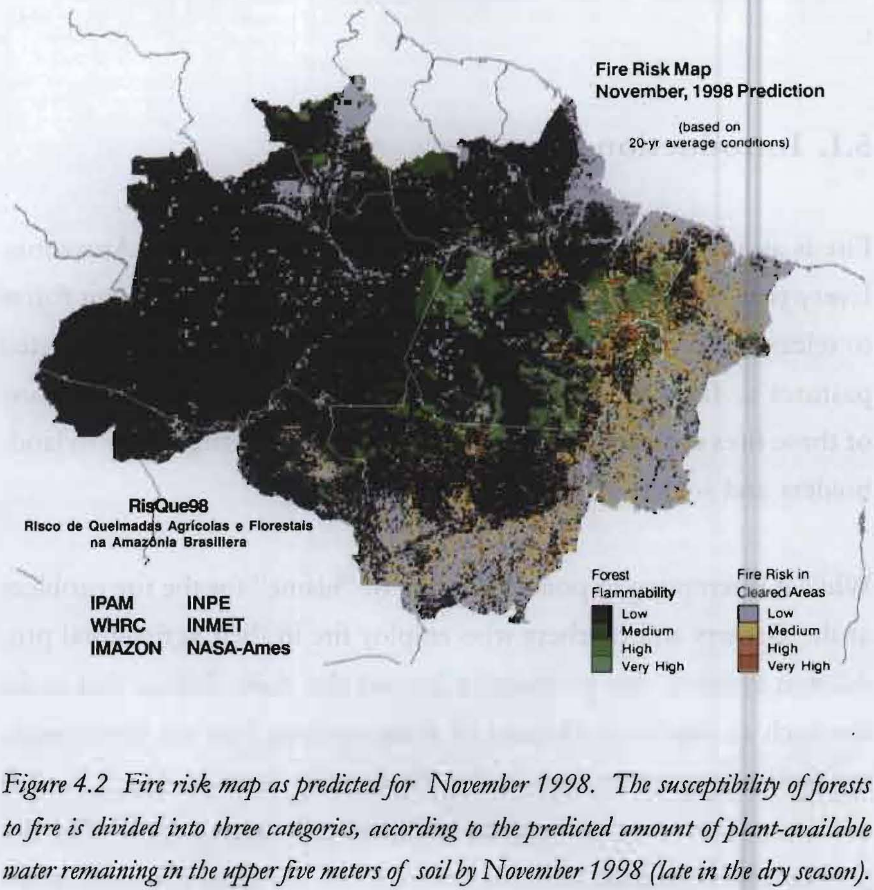

Figure 4.2 Fire risk map as predicted for November 1998. The susceptibility of forests to fire is divided into three categories, according to the predicted amount of plant-available water remaining in the upper five meters of soil by November 1998 (late in the dry season). Forests with no water remaining were classified as "Very High Risk", those with 0 to 150 mm were called "High Risk", and those with 151 to 300 mm of water were called forests of "Intermediate Risk". The risk of deforested land catching fire was based on the frequency of hot pixel occurrence as measured in 1997.

5. Solutions to the Amazonian Fire Problem

5.1. Introduction

Fire is an inseparable feature of the agriculture frontier of Amazonia. Every year, millions of farmers and ranchers ignite tracts of cut forest to release crop-fertilizing ash onto the soil, or set ablaze weed-infested pastures to favor grass production. The problem of fire is that many of these fires escape their intended boundaries with large costs to landholders and society at large.

While it is tempting to point the finger of "blame" for the fire problem at the farmers and ranchers who employ fire in their agricultural production systems, this perspective ignores the many factors that make fire such an important element of these systems. Fire is a very appealing land management tool in the Amazonian frontier, where land is abundant, but labor and capital are usually in short supply. The fire problem will continue until fire ceases to be the most efficient means of growing subsistence crops, converting forest to cattle pasture, and reducing weed populations in these pastures. Agricultural and forestry systems that do not depend upon fire are currently outcompeted by fire-dependent systems throughout most of Amazonia.

The development of solutions to the problem of fire in Amazonian must therefore begin with the acknowledgment that fire is currently a chronic, annual feature of rural Amazonia. Accidental fire presents an episodic "emergency" to Brazilian society only when severe drought and/or accelerated fire-dependent land-use activities greatly increase the occurrence of accidental fires during a particular period of time.

However, even these "emergency" situations take place every 2 to 4 years (1988, 1992, 1995, 1997 and 1998), thereby stretching the concept of "emergency". Solutions to the fire problem must harness the public concern that arises during emergency years and redirect it into political processes that alter the long-term development pathway of the region. It is only in the context of a coherent, long-term approach that we can expect a gradual decrease in the use of fire by rural producers, and a gradual increase in landholder investments in prevention of accidental fire. It is only in tandem with such long-term approaches to the fire problem that emergency fire programs for years of particularly high fire risk begin to make sense.

In this chapter, we analyze the options for reducing the occurrence of accidental fires in Amazonia. We begin with a brief review of the techniques and community-level approaches that are currently employed by Amazonian farmers and ranchers to combat accidental fire on their properties, and the research and education needs associated with the testing and dissemination of these approaches. The considerable cost of implementing most of the techniques and approaches is then discussed within the context of cost-benefit analysis of investments in the prevention of accidental fire. Since many of the benefits of landholders' investments in fire prevention accrue to society at large, or to neighbors, strategies to reduce these losses cannot rely on the enlightened self-interest of the landholder alone, particularly in the absence of effective mechanisms to enforce existing legislation. Instead, such strategies must place restrictions on the ways in which rural landholders use their land, and must provide economic incentives that encourage additional investments in fire prevention, or reductions in the use of fire as a land management tool. The legislative and financial opportunities for encouraging these changes in landholder behavior are analyzed in this context. The potential role of emergency planning is also discussed.

5.2 Current efforts to prevent and suppress accidental fire

Fire prevention and suppression techniques employed by landholders

Are accidental fires so pervasive in Amazonia because of a lack of appropriate techniques for fire prevention and suppression? To read the media reports of the Roraima fires of 1998 one would think that the answer to this question is "yes". In fact, effective techniques for preventing and controlling accidental fires in rural Amazonia are available and widely used, but the knowledge of these techniques resides among the farmers, ranchers and loggers who are faced with economic losses to fire every dry season. This "indigenous" knowledge of fire management techniques has received little attention by researchers, and remains to be tapped by government institutions responsible for defending public interests in Amazonian natural resources. This knowledge should be rigorously tested, documented and incorporated into training programs for extension agents, agronomists, foresters and other natural resource professionals. This section provides an overview of these techniques, learned through hundreds of interviews with landholders conducted by IPAM. A more detailed description of these techniques is found in Appendix II.

The first rule of fire prevention and control is that it is much easier and cheaper to prevent accidental fires from occurring than to put them out once they escape the limits of the intended burn area. Small, strategic investments made in fire prevention can thus avoid the need—and the expense—of assembling large groups of people and equipment to combat fires under emergency conditions.

Fire requires abundant, dry fuel close to the ground, lots of oxygen, and a source of ignition. Cattle pastures are the most flammable ecosystems in Amazonia because forage grasses exposed to the full drying action of the sun are highly flammable (Uhl and Kauffman 1990), and the winds that sweep across large pasture clearings provide ample oxygen. Techniques for preventing and controlling accidental fire must remove at least one of these essential fire ingredients in order to be effective. The options for removing these ingredients are many, with varying requirements for labor, capital, and equipment.

Vegetation can be protected from fire by strips of land from which fuels have been removed. These "firebreaks" are the single most important technique for defending vegetation against accidental fire, but they are also the most expensive to implement. As illustrated in Chapter 3, a small-scale rancher would spend half of his anticipated profits from cattle production in the manual preparation of firebreaks around a 100-hectare pasture. Hence, education programs that encourage farmers and ranchers to invest in the preparation of firebreaks run the risk of encouraging practices that are not economically viable (see, for example, Table 3.13), thus discouraging landholder investment in fire prevention.

Fire education campaigns should encourage those fire prevention and control practices that are relatively cheap to implement. One of the most underutilized, inexpensive techniques for containing fire is the back-burn, in which a fire line is ignited along the downwind border of an area that is being intentionally burned. This back-burn has the effect of widening the downwind firebreak at a very low cost. Back-burning can therefore reduce the expense of preparing the downwind firebreak (Appendix II).

The "cool burn", in which intentional burns are set when vegetation moisture content is high, or late in the day, as the relative humidity of the air begins to climb, may appear to be an inexpensive technique for reducing the risk of accidental fire. However, there is a large cost associated with the cool burn, in that less of the vegetation being burned is converted to ash. Farmers can suffer reduced crop harvests, for example, if large portions of their slash and burn plots fail to burn effectively (Appendix II).

Perhaps the most effective technique for controlling the spread of forest fires is the forest firebreak line. Subsistence farmers across Amazonia control the low, slow-burning fires that spread into their forests by sweeping the forest floor free of organic debris along narrow trails that circumscribe the forest fire. These forest firebreaks impede the spread of forest fires at a much lower cost than military troops and water-bearing helicopters.

Local governance among neighbors and farm communities

The greatest challenge of fire prevention and control techniques is to reduce the amount of money, labor, and/or time needed to implement them. One of the most promising ways of reducing the costs of these techniques is through cooperation between neighboring landholders, or among members of farm communities. The types of cooperative agreements that can be made range from an agreement between two neighbors to notify each other when an accidental fire is spotted, to a full-fledged community fire ordinance that defines the ways in which fire can be used by community members, and the penalty imposed for non-compliance. We present here a brief description of the main types of agreements, and describe the community fire ordinance of Del Rey, a farm community in eastern Pará state.

Agreements between neighbors: The easiest fire agreement to make is between two neighboring landholders with a common interest in reducing the occurrence of accidental fire. Through a single conversation, they can agree to advise each other of escaped fires and of the dates of intentional fires, to help each other contain intentional fires on the day of the burn, and share the costs of making firebreaks along common property boundaries. Such agreements take place informally between landholders across Amazonia, but their effectiveness in reducing accidental fire remains to be studied. Our interviews of Amazonian landholders indicate that this is virtually the only type of agreement that is made by large scale landholders, since they are rarely organized into close-knit communities as small-scale farmers sometimes are.

More sophisticated agreements between neighboring landholders can include the spatial planning of different agricultural systems to reduce fire risk. Neighbors can agree to leave large blocks of continuous forest across adjacent portions of their land to impede the spread of escaped fires, and they can agree to position their deforestation plots on contiguous land, thereby reducing the amount of firebreak needed to contain these fires.

The potential of neighbor accords to contain fire is illustrated by an example from the Del Rey community, in which two neighboring farmers—Vicente and Arnaldo—decided to place their annual slash and burn plots on adjacent land. They prepared firebreaks together, and conducted the burn together, with one farmer igniting a back burn along the downwind boundary and the second igniting the downwind fire. Immediately following the fire, they inspected the forest areas adjacent to the plot and found five locations where the fire had escaped the burned plot. Each of these escaped fires was arrested at the firebreak that the farmers had made ten meters into the interior of the forest.

Community accords: There are numerous types of accords that can be made by communities of small-scale farmers to regulate the use of fire by community members and to plan community-level responses to accidental fire. Such accords have been developed by farm communities across Amazonia. Many communities have established "brigadas voluntárias" (voluntary fire brigades) to help suppress accidental fires. The Amazonian Working Group (GTA), a network of over 300 organizations, conducted a large-scale program of field courses in 1998 encouraging farm community leaders to form fire brigades in their communities. More complex accords can regulate the types of burning that are allowed by community members, the measures that must be taken to prevent accidental fires, and the community-level responses to accidental fires. We illustrate both the potential and the problems associated with community-level accords through an analysis of the Del Rey farm community's fire regulation.

The case of Del Rey

Like many farm communities on the Amazon frontier, Del Rey was formed when poor farmers from Brazil's drought-stricken Northeast emigrated to Amazonia and began to carve a living out of forest land through slash and burn agriculture. The original group of farmers was expelled from its new land by a logging company, then allowed to resettle in the same area in 1989 after the forest had been logged. Two years later, as the 1991-92 El Niño episode provoked severe drought in Del Rey and across eastern Amazonia, the community's 9,000 hectares of forest turned into a tinder box, and virtually all of it burned as agricultural and pasture fires went out of control.

In response to the Del Rey fire crisis and numerous other accidental fires on the lands of farm communities, the Rural Workers' Union of Paragominas (Sindicato de Trabalhadores Rurais de Paragominas) invited IPAM and WHRC to work with the farmers of Del Rey to reduce the incidence of accidental fire. The first part of the resulting collaborative project involved mapping the community boundaries, including the individual family plots and burned areas, using satellite imagery. The map generated was also used to start legal land titling procedures at the land reform agency (INCRA).

The techniques used by farmers of Del Rey to prevent accidental fire were documented by studying the slash and burn cultivation cycle in 11 family-plots. Although virtually all of the farmers in Del Rey knew how to make firebreaks to prevent their agricultural fires from escaping, many of them did not employ firebreaks because they were not prepared to invest the time and energy required. Several days are needed to clear firebreaks around a typical farmers' slash and burn plot. Even if firebreaks were made, many of the farmers chose not to cut down the dead trees in their forests. These dead tree "snags" increase the risk of accidental fire since they can fall across firebreaks, but they are dangerous to fell because of the risk of falling branches.

At Del Rey, the most promising approach to reducing the occurrence of accidental fires is improved communication between neighbors. Many accidental fires originate when an agricultural plot is burned without the owner of the neighboring farm knowing about it. A major dispute among neighboring farmers arose after one such accidental fire in the 1995 dry season, prompting the Del Rey farmers to convene a community-wide meeting. They decided to establish a fire policy to reduce the incidence of accidental burns in a remarkable exercise of local governance. This effort was translated into a set of regulations, discussed in successive meetings during which they drafted and approved the "Del Rey Colony Fire Regulation" (Fig. 5.1).

This regulation (Figure 5.1) requires that farmers provide eight days advance warning to neighbors of the date of their burn, and that they prepare firebreaks in both forest and pasture adjoining the planned new clearing. It also recommends that agricultural clearings should not be placed upwind from highly flammable ecosystems such as pastures, that neighbors clear and burn their plots at the same periods, and that standing dead trees likely to fall outside of the clearings be felled prior to burning. If an escaped fire damages a neighbor's property, the regulation requires compensation following a community proceedings to identify the responsible party and ascertain the extent of damages. In the 1997 dry season, the Del Rey Fire Commission, a five-person committee established by the fire ordinance, supervised eight intentional fires in the community, and mediated disputes involving accidental fire. In one case, the commission decided that a farmer had to pay his neighbor one thousand fence posts as compensation for damages wrought by his escaped fire.

It is too early to tell if the Del Rey Fire Regulation will provide a long-term solution to the problem of accidental fire in the community. The success of the regulation thus far can be traced to the dedication of three farmers who tirelessly organize and attend meetings, and encourage other community members to participate. The Regulation requires substantial commitment of farmers' scarce time to implement, particularly to meet the firebreak requirement, and we do not know if

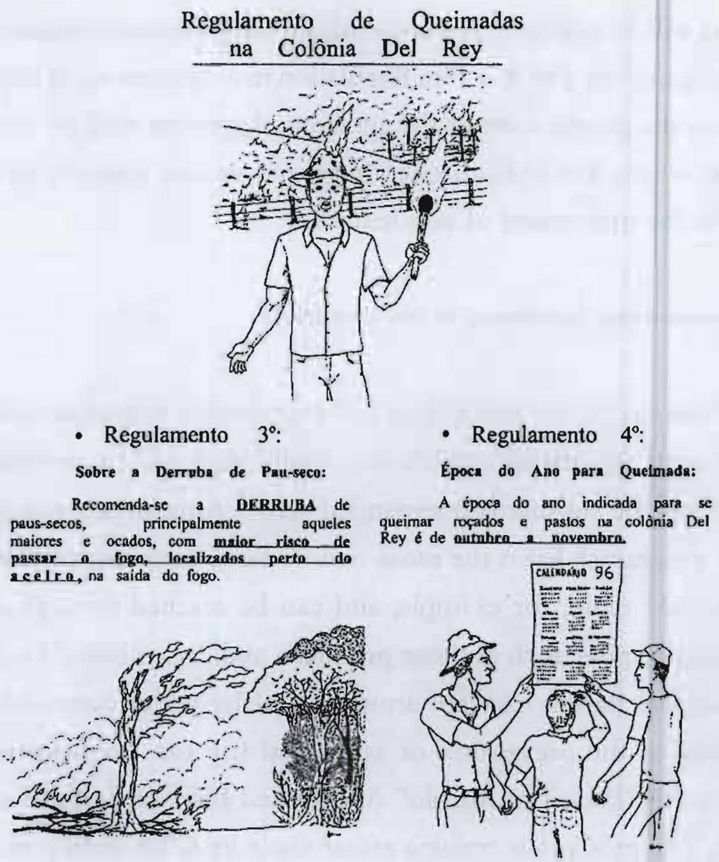

*Figure 5.1. The cover and two sample pages from the Del Rey Colony Fire Regulation booklet (*Regulamento de Queimadas na Colônia Del Rey*). Regulation three recommends that standing dead trees that are close to the fire break be cut down prior to burning. Regulation four recommends that agricultural and pasture fires be conducted in October or November. Other regulations are obligatory, including the preparation of fire breaks along the downwind boundary of agricultural fires.*

farmers will be willing to continue the annual investment in firebreaks. The future of the Del Rey Fire Regulation may depend upon improvements in the productivity of the agricultural systems used by the community, which would both encourage and enable farmers to invest more in the prevention of accidental fire.

How to encourage investments in fire prevention?

Could the use of fire prevention and suppression techniques, and the adoption of accords by neighboring landholders and by communities of farmers, be substantially expanded across Amazonia through education programs? Even the most remote farm communities have access to AM radio, for example, and can be reached through educational radio spots, such as those produced and disseminated by IPAM. Educational handbooks are another tool by which successful approaches to the prevention of accidental fire can be disseminated, such as the "Fogo Controlado" (Controlled Fire) series produced by IPAM. The prodigious training effort made by GTA during the 1998 fire season is another example of how to communicate to rural producers the importance of investments in fire prevention. These dissemination efforts represent important research opportunities to measure the changes in farmer and rancher behavior that occur in response to information on fire. Of greatest interest is the long-term sustainability of any behavioral change. Educational campaigns may cause a temporary pulse in farmer investments in firebreaks, for example, which diminishes in subsequent years because of its considerable cost.

An additional constraint on the potential of education programs to reduce the occurrence of accidental fire is our lack of knowledge of the most cost-effective techniques and institutional arrangements for preventing and controlling accidental fire. The fire prevention and suppression techniques described above are being used in rural Amazon, but their relative effectiveness has not been studied, nor have their costs and benefits been analyzed. We do not know the circumstances under which it is economically advantageous for landholders to invest in firebreaks, fire surveillance, and emergency fire suppression plans. Such information is essential to enable public authorities to allocate scarce budgetary resources for fire prevention where they will be most effective.

We believe that there are no easy short-cuts around the formidable organizational and economic barriers that prevent groups of Amazonian farmers or ranchers from joining forces to reduce the occurrence of accidental fire on their land. A lack of leadership, low levels of community participation, and community instability may present the greatest barriers to the implementation of community fire regulations in communities across Amazonia. A single recalcitrant farmer who refuses to pay his neighbor for damages caused by an escaped fire can undermine a fire regulation that required repeated community meetings over several months to establish.

The development of the capacity for local governance within a farm community is a long-term process, which can be accelerated through sustained inputs from dedicated, well-trained professionals willing to spend much of their time working directly with communities under harsh field conditions. There is a dearth of such professionals in Amazonia. Many of the technical schools and university programs that are training agronomists and foresters have curricula aimed at industrial production systems. Amazonia's agronomists and foresters typically know very little outside of their discipline, and virtually none of these young professionals are trained in the management of fire within agricultural or forestry production systems. A new generation of extension agents and researchers is needed, who are capable of integrating a variety of disciplines, and are interested in devoting large amounts of time working directly with communities of farmers to address the challenge of rural development. In particular, communities need help in developing the capacity for self governance, not just for fire prevention but for the full range of collective decision-making. Alliances may also be sought with other social organizations, such as churches and schools.

Community-based approaches to the reduction of accidental fire require more than just a new generation of multi-disciplinary, field-oriented extension agents and researchers. In addition, the economic and legislative context in which rural development proceeds also must change. Economic and legislative tools implemented by government can create an environment in which rural producers shift to agricultural systems that are less dependent upon fire, or are encouraged to invest in fire prevention techniques, and organize themselves to reduce the occurrence of accidental fire. We analyze here some of the economic and legislative approaches to the reduction of accidental fire. We preface this analysis with a brief discussion of the economic decision-making of producers on the Amazonian frontier.

5.3 Fire in the context of the Amazonian frontier

Fire and frontier development

Fire is the quintessentially "extensive" land management tool of the tropics. It is wasteful of nutrients, it is wasteful of forests, and it threatens investments made in agricultural and forestry production systems. But it is also a fast and cheap way of clearing land, providing nutrient-rich ash to the soil and of reducing populations of weeds and pests. It makes economic sense to use fire when land and forest is abundant and inexpensive. Fire is therefore an intrinsic component of the current model of occupying rural Amazonia, in which natural resources such as land and forest are viewed as virtually unlimited commodities that can and should be mined, instead of as scarce resources that must be carefully managed. The long-term solution to the fire problem of Amazonia will depend upon the emergence of an alternative model for regional development that favors greater investments of labor and capital in smaller areas of land.

The current "mining" approach to Amazonian economic development can be understood within the context of frontier evolution. Extensive land-use practices—such as large-scale cattle production, logging and slash and burn agriculture—are common in the early stages of the evolution of the agricultural frontier, when the high cost of transport prohibits market-oriented intensive agriculture, as represented in Fig. 5.2a (Boserup 1965, Van Thunen 1866 (cited in Schneider 1993)). In this scenario, land is available to those who are willing to occupy it and practice extensive forms of land-use, and the main limiting factors to agricultural and forestry production are labor and capital—land and forest resources are effectively free. In this setting there is little incentive for ranchers, loggers or farmers to invest in the prevention of accidental fires that would damage their "value-less" forest resource.

As the frontier evolves and marketing systems become established, land prices increase as the profitability (and intensity) of land-use systems rises (Fig. 5.2b). Subsistence farmers either join the market economy, or they are bought out or forced off their land by market-

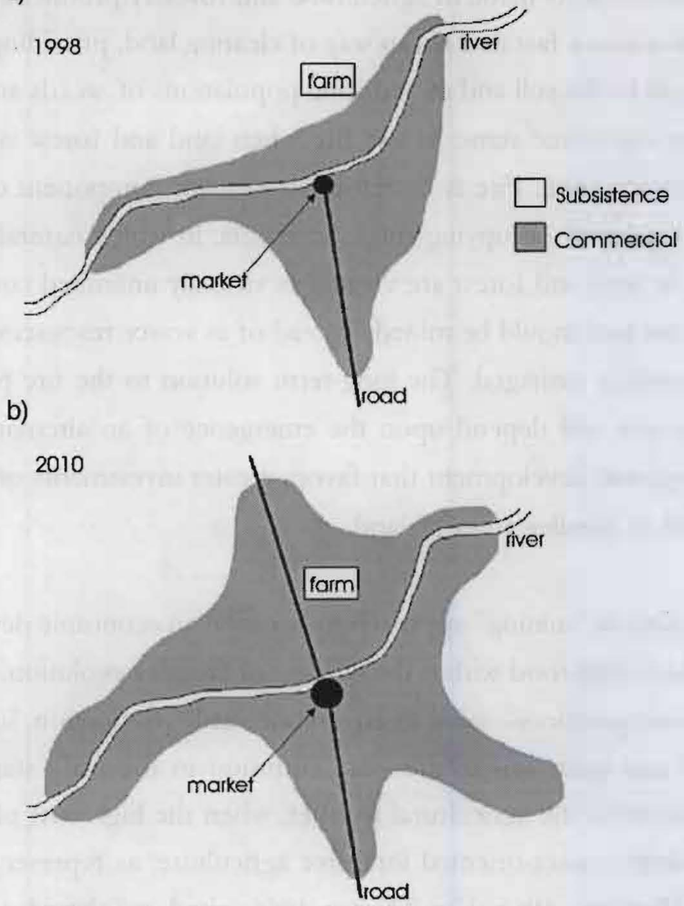

Figure 5.2A,B Like any frontier, Amazonia is punctuated by markets around which intensive, market-oriented agricultural systems develop (A). With increasing distance from the market—or increasing difficulty of access—land-use systems are less intensive, and tend to focus more on subsistence activities and extensive cattle production systems that depend upon fire as a management tool. Over time, road systems are improved, electrical grids are extended out into the countryside, and the zone of market-oriented production expands (B). We hypothesize that the use of fire declines through this process of agricultural evolution, and that the tendency to invest in fire prevention increases.

oriented landholders, and more profitable agricultural systems are established, raising the value of the land. Landholders turn away from the use of fire in their land management systems because it is difficult to control, it threatens expensive investments on the land, and alternatives to fire's role as fertilizer, weed control, and pest control become more available in the form of chemical fertilizer, herbicide, and tractor-drawn machinery.

The costs and benefits of fire prevention: a conceptual framework

The logic of fire on the Amazonian agricultural frontier can best be understood in terms of the costs and benefits of the use of fire, and of investments in fire prevention. Fire can confer benefits to landholders by quickly converting nutrients tied up in biomass into fertile ash, by favoring grasses over weedy invaders in cattle pastures, by reducing insect and pathogen populations, and by clearing away woody debris following forest felling in preparation for agriculture. Against these benefits, however, are several costs of fire associated with the loss of plant nutrients, and the risk that fires will escape and damage fences, forage, crop fields, tree plantations and forests. There are also costs to neighbors and to society in general which may have little bearing on landholder behavior, including local production losses on neighboring land as well as the health problems provoked by smoke, damage to power lines, airport closures, and, at a global scale, the release of carbon to the atmosphere that takes place when biomass is burned. If we assume that Amazonian landholders use fire in a rational way, then they will use it only when the private benefits of burning outweigh the private costs of burning. The tendency to use fire as a land management tool is therefore likely to diminish as the productive value of the land—and the potential losses associated with accidental fire—increase (Fig. 5.3a). For example, ranchers who plant pastures with fire-sensitive forage grasses (e.g. *Brachiaria brizantha*) sometimes abandon the use of fire as a pasture management tool.[15]

By the same token, the rational landholder will only invest in the prevention of accidental fire to the point at which an additional investment in prevention generates an additional benefit (in the form of lower fire risk) of at least equal value. In other words, investments in fire prevention will be made up to the point at which the marginal private cost of the investment is equal to the private marginal benefit it confers in the avoidance of fire-related damages. In general, we expect landholders to exhibit greater willingness to invest in fire prevention (through firebreaks and other practices) and fire control (i.e. efforts to contain fires that have escaped beyond the area which the farmer intends to burn) when they perceive the probability of accidental fire to be higher, for instance due to prolonged drought or the clearing of adjacent land by farmers practicing slash and burn agriculture. Similarly, landholders who have invested heavily in the fire-sensitive forage grass, *Brachiaria brizantha*, or high value crops and infrastructure, should be more willing to invest in fire prevention in order to protect this investment, because they have more to lose (Fig. 5.3a). Any understanding of the economic logic of fire use and fire prevention in Amazonia must take into account another very important variable: neighbors. When one landholder ("X") invests heavily in firebreaks to prevent his management fires from escaping or to prevent his fields and forests from catching fire, part of the benefit of these investments is conferred to his neighbor ("Y"), whose fields and forests are at lower risk of catching fire because of these investments in

[15] *A. Alencar, personal observation.*

fire prevention. If the landholder Y decides to make no investments in fire prevention, then landholder X's investments in fire prevention will bring lower private benefits, because X's fields and forests run the risk of catching fire from Y's property. The benefits derived from investments in fire prevention are greatest when both landholders invest equally in fire prevention practices, such as firebreaks along their common property boundaries.

Benefits of investments in fire prevention accrue to private landholders, their neighbors, and to society, but the cost is borne only by private landholders. Currently, all of the onus of fire prevention is on the backs of private landholders, which produces a sub-optimal investment in fire prevention. In effect, we expect landholders to discount the potential damages of fire escaping from their land to neighboring holdings, particularly in the absence of effective mechanisms for claiming compensation for fire damages from those responsible. Similarly, landholders may discount or entirely ignore the broader impacts of fire on non-market forest values, such as carbon storage, hydrologic services, soil and water conservation, or the health impacts of smoke. The discrepancy between the private and social marginal benefits of investments in fire prevention and control is shown in Fig. 5.3b, which also shows the higher level of investments in prevention and control that would be considered optimal from a societal perspective.

The gap between private and social losses associated with accidental fire is not fixed and can be reduced by appropriate regulations and institutional arrangements, such that private landholders "internalize" the full social costs and benefits of fire prevention. This must be the focus of initiatives to reduce burning in Amazonia.

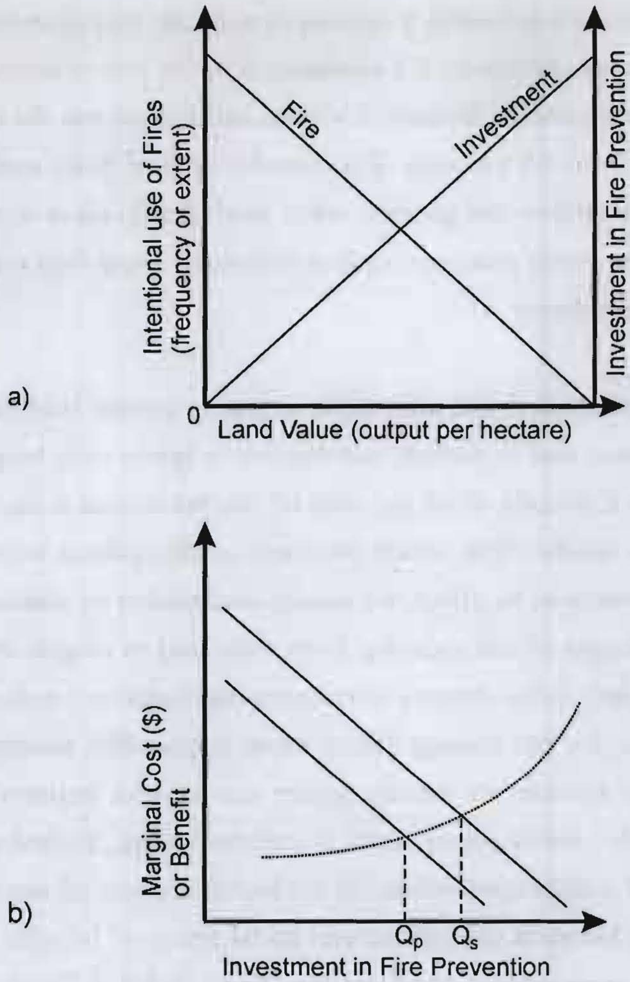

Figure 5.3A,B Qualitative model of the costs and benefits of fire prevention. A. Farmers and ranchers are less likely to use fires as part of their management system as the intensity and value of production increases. The willingness to pay for fire prevention increases as the intensity and value of production increases, because the economic losses associated with accidental fire are higher in the more productive system. B. The optimal level of investment in fire prevention is where the marginal cost of further investments in prevention is equal to the marginal benefit of this investment. Private landholders will generally choose a lower level of investment in fire prevention (Q_p) than the socially optimal level (Q_s), however, because they do not consider certain future benefits of their investment, such as reduced risks to neighbor's land, the protection of biodiversity, and future timber values.

5.4 Public policies

Public policies are the tools by which government can reconcile the collective interests of society with the private needs and ambitions of society's individual members. They are therefore an important part of any strategy to address the Amazonian fire problem. As a preface to this discussion of public policies, we should remember that fire is not just another environmental issue in the Amazon. Rather, it both influences and is affected by a broad spectrum of the region's rural development policies. As an essential tool of extensive land use that reduces the viability of more intensive land uses, fire is at once both the result and the cause of a development pathway based on natural resource mining. Efforts to change the model of natural resource use from its current mining approach to a more "sustainable" basis will require better integration of Amazonian policies aimed at promoting economic development and settlement with those designed for conserving natural resources. In this sense, the cross-cutting nature of the fire problem represents an opportunity to reconcile interests in the region's economic development with interests in natural resource conservation.

A strategy for the formulation of truly integrated development and conservation policies for Amazonia should be guided by the logic of efficient natural resource utilization, and equitable sharing of rights, responsibilities and returns from their use. Policies are needed that provide incentives for increased agricultural productivity on deforested lands while at the same time providing disincentives for reckless uses of forested lands. Some of the key elements of this policy integration can be identified from the literature on Amazonian rural development (Mahar 1989, Hecht 1985, Schneider 1993, Schmink and Wood 1992). These elements include land tenure, infrastructural planning, protected areas, and credit programs.

Land tenure policies should be aimed at granting legal titles to land in areas of agricultural settlement. Land title given to settlers helps them acquire access to credit needed to make investments in their land, which in turn creates disincentives for fire use and incentives for fire prevention. Legal ownership of land also favors more intensive forms of land use because it can decrease the risk of government appropriation and increase the confidence that benefits of investments in the land will accrue to the landholder. Land tenure policy must be designed to prevent, however, the encouragement of land speculation, since rapid land titling can make it easier for squatters to sell land at a profit, and move on to the next frontier. This practice of falsifying land titles ("grilagem") is itself one of the driving forces of frontier expansion in Amazonia (Schmink and Wood 1992).

We interpret all government decisions to establish infrastructure in unsettled forest regions of rural Amazonia as *de facto* policy decisions to expand the agricultural frontier, indirectly exacerbating the Amazon fire problem, and the reckless use of natural resources generally. The construction of all-weather roads, electric power grids, waterways, railways, gas pipelines, hydroelectric dams and the concession of industrial mining permits brings people into remote forest regions, and brings new lands into the frontier and onto the land market. This frontier expansion drives down the value of land that is already accessible, and favors extensive forms of agriculture that generate high returns to labor (or to capital invested), but which also require a continuing supply of new, cheap land to be economically viable (Schneider 1993). Infrastructural investments should focus on Amazonian regions that are already settled, where they can favor land-use intensification. For example, the improvement of road networks in settled regions reduces transport costs, thereby increasing the profitability of market-oriented agricultural production systems.

Increases in the area of forest effectively protected from development also impedes frontier expansion. The Brazilian government's recent commitment to set aside 10% of the Amazon forest as protected nature reserves and parks could reduce the availability of cheap forestland. It remains to be seen if this commitment will be accompanied by concrete governmental actions. The existing requirement that 80% of private properties of 1000 hectares or more must be kept in forest reserves could also act to slow the rate of frontier expansion. Here, again, the legislation far exceeds the government's current capacity for implementation. This law could be used to directly reduce the flammability of agricultural landscapes in Amazonia if it were modified to require that these forest reserves circumscribe the property's agricultural lands, thereby reducing the likelihood that escaped agricultural fires will burn neighboring properties.

Finally, agricultural credit programs should encourage the intensification of land-use systems by supporting technical assistance, marketing facilities, improved transportation systems and other measures designed to build the capacity of local institutions to engage in commercial enterprises. Credit programs must be developed in tandem with programs that provide greater protection to forests. Otherwise, increases in the profitability of agricultural production systems can act to stimulate forest conversion to agricultural land. This topic is discussed in greater depth in the section on financial approaches, below.

The defense of the public's interest in Amazonian natural resources—and the damages to natural resources inflicted by fire—will require both legislative and economic policy approaches. We now analyze the potential of each of these approaches in addressing the Amazon fire problem.

Brazilian environmental legislation made important strides in 1998. Until recently, IBAMA did not have the legal authority to impose fines or other penalties on environmental law breakers, and most cases of illegal logging or burning stalled in the courts. The Environmental Crimes Law, approved by Congress in February of 1998, granted this authority to IBAMA and other environmental agencies.[16] This legislation was a fundamental step in strengthening environmental regulatory agencies in their efforts to implement environmental legislation. However, the portion of the Environmental Crimes Law that would have made forest fires illegal (without adequate fire prevention and control safety measures), was vetoed by the President. With this veto, the use of fire in and near forests without a permit and without adequate safety measures reverts to the Forest Code of 1965,[17] in which this illegal fire use is punished as a "penal contravention", similar to a misdemeanor, instead of as a "crime", which is similar to a felony in US law. In other words, from a legal standpoint, the reckless use of fire in forests is a lesser offense than damaging someone's ornamental plants (a crime that is punishable by a prison sentence of 3 to 12 months.)

From one perspective, this deficiency could be overcome on the basis of the principles established under the National Environment Policy Act,[18] which states that a person (or people) who causes damage to the environment must pay for these damages. For example, a landholder who sets his pasture on fire and damages a neighbor's property or a forest, is legally responsible for all of these damages, and should compensate the neighbor or the government. In practice, this legisla-

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[16] Law 9605/98.
[17] Law 4771/65
[18] Law 6938/81

tion is very difficult to apply, since there is no legal precedent establishing values for environmental services performed by forests, and most of the people affected by accidental fires have insufficient funds to hire experts to document fire related losses. It is also extremely difficult to prove how fires started and, hence, to assign responsibility. This important legislation might be strengthened by assigning responsibility collectively. For example, the federal government could hold a local authority, such as a community or municipality, responsible for society's losses stemming from forest fire, forcing this authority to determine a practical mechanism for penalizing the private landholders who perpetrated the fire.

The Presidential Decree of July 1998[19] establishes regulations for the use of fire throughout the country and incorporates some innovative concepts, such as recognition of the community collective burn ("queima solidária"), and the need for temporary suspension of fire permits in some regions when fire-risk is exceptionally high. Like the Forest Code of 1965, the Decree establishes that rural producers are only allowed to burn their land after they have obtained a permit from an environmental agency, but adds requirements that make it virtually impossible to implement. For example, if a small-scale farmer wants to burn 2 hectares of his land to plant manioc and corn, he must go to the nearest environmental agency (IBAMA, or a state or municipal environmental agency) 30 days before the scheduled date of the burn, fill out a form with information about the burn to be performed, demonstrate legal ownership of the land to be burned, agree to make firebreaks of 3 meters width around the burn area, and state that sufficient people and equipment will be available to contain the fire on the day of the burn. The typical small-scale farmer of rural Amazonia,

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[19] Decree 2661/98

however, is probably unaware of the requirement to acquire authorization to burn, lives tens of kilometers from the responsible environmental agency, possesses no means of transportation other than his legs, has no legal title to his land, and relies on family labor to prepare firebreaks and control escaped fires.

The Decree also states that the responsible environmental agencies should process the fire permit request within 15 days of the solicitation, conducting a field inspection in the area to be burned if this area contains forest remnants or if it adjoins protected conservation areas, and sending staff to accompany the burn. The implications of this statement are enormous when one considers that virtually all forest felling conducted in preparation for slash and burn agriculture contains "forest remnants", and would therefore require a field visit from the local environmental agency. To fulfill this element of the Decree would therefore require hundreds of thousands of field inspections each year! One of the biggest problems in the implementation of environmental legislation in Amazonia is the lack of institutional capacity to execute it, and this Presidential Decree is no exception.

Despite its numerous shortcomings, the Presidential Decree of 1998 provides an example of a mechanism by which civil society can influence legislation and, eventually, result in effective legislation. In April, 1998, a regional workshop on fire, held in Belém, brought together representatives of non-governmental organizations, government agencies, and the regional finance community to discuss the fire problem, and its potential solutions.[20] The "Belém Charter" that emerged from this workshop was presented to the Brazilian Government, and was

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[20] Most of the organizations represented were non-governmental organizations that work with rural farmers.

acknowledged in a public hearing of the National Congress as "the basis of the IBAMA approach to the fire problem".[21] This document also appears to have influenced the Presidential Decree on fire, which recognizes "solidarity burning", as recommended in the Charter. The eventual emergence of sound fire legislation in Amazonia will depend upon continued well-orchestrated inputs from civil society.

Economic instruments

Governments around the world rely increasingly on economic incentives ("market-based instruments") as a key tool of environmental policy. Well-designed economic instruments can be a very efficient means of protecting the environment, whether through pollution taxes and user fees, tradable permits, reform of environmentally "perverse" subsidies, or other market-oriented measures. In the case of Amazonian fire, these policies hold a distinct advantage over the current punitive, legislative approaches to fire described in the previous section. The economic "carrots" that could be offered to Amazonian producers to encourage investments in fire prevention and in fire-sensitive agricultural systems, may hold far greater potential for changing land-user behavior than the legislative "sticks" designed to reduce fire occurrence through fines and other punishment. Currently, none of the economic programs available to Amazonian farmers and ranchers are explicitly designed to reduce accidental fire.

There are four general categories of economic instruments for addressing environmental problems that could be applied to the problem of Amazon fires. Pollution taxes are used to make the polluter pay for the

[21] Eduardo Martins, President of IBAMA.

environmental damages that they inflict, thereby incorporating societal damages of pollution into the economic decision making of the producer, and could be applied to Amazon fires by making landholders pay to burn. Such an approach clearly exceeds the current institutional capacity of the government, however. Tradable permits are used to reduce society's aggregate damages below an "acceptable" level, and could be applied to the Amazon fire problem as a way of putting a limit on the total number (or area) of fires. This approach is also limited in Amazonia by insufficient institutional capacity. A third category of economic instruments is called "market facilitation", and includes liability insurance programs. Fire liability insurance, for example, could be required of landholders who acquire government agricultural credit or subsidies, with premiums reduced for those who demonstrate investment in fire prevention practices. Such programs would be vulnerable to arson, as landholders try to claim fire-caused damages to their property for fires that they deliberately ignited. Subsidy reform, a fourth type of economic instrument, is the focus of the discussion presented here. This approach seeks to modify credit and subsidies programs to encourage investments in fire prevention practices, and in fire-sensitive production systems.

Existing rural credit policies-such as the Constitutional Fund of the North (FNO), the Agrarian Reform Support Program (PROCERA), and the National Program for Strengthening Family Agriculture (PRONAF)-could include support for investments in fire prevention and control techniques and equipment in their programs. Such changes would be easy to make because these policies are legally autonomous. In the case of financial support programs directed specifically toward rural communities, such as the Program for the Support of Agricultural Production in Amazonian Communities (PAGRI), the incentive could be designed to encourage the adoption of fire use regulations by funding community-level infrastructure and equipment needed to manage fire, and by covering the expenses of establishing and maintaining local organizations for fire prevention and control.

Small changes could also be incorporated into the fiscal and taxation policies that already exist for the region. Fire utilization should be prohibited in agricultural projects approved through the Amazonian Investment Fund (FINAM). Businesses throughout Brazil that draw on this fund and enjoy income tax exemptions of up to 75% over a ten year period, could be threatened with removal of this tax holiday if they fail to exclude the use of fire from their enterprises. Tax exemptions (ICMS and IPI) on the purchase of equipment could also be used to encourage communities to adopt fire regulations, and to create volunteer fire-fighting brigades at the community or municipal level.

In Table 5.1, we have summarized possible changes in the Amazon region's main financial and fiscal programs that would provide incentives for landholders to invest in the prevention and control of accidental fire. The main effect of these changes would be to reduce the cost of such investments for the region's farmers and ranchers. In the long term, such policies could be used to encourage the elimination of fire from rural production systems. This step would require large investments in technological alternatives to fire, such as increased use of fertilizer and machinery.

These economic approaches to the fire problem could be used over the long term to encourage the substitution of fire-dependent forms of land-use with more intensive production systems on land that is already deforested. In the context of an overall policy reform that improves transport systems, energy supplies, health services and education systems in old frontier regions instead of encouraging the expan-

Table 5.1. Summary of changes in existing economic policies that could reduce fire use and accidental fire in agricultural and forestry production systems.

Policy	Proposed Change	Anticipated Effect	Producers Affected	Agencies Involved
FNO (Special, Normal, Prodex, Prorural)	-finance fire prevention and control methods and equipment -incorporate fire insurance -prohibit burning during high risk periods -finance communities that propose fire regulations	-reduce cost of fire prevention and control -encourage employment of fire prevention techniques -reduce fire use in high risk periods -encourage community fire accords	-small holders -medium and larger landholders -reforestation firms -logging firms	BASA, SUDAM, EMATER
PROCERA (already operational)	-finance fences, firebreaks, and pasture recuperation -prohibit burning during high risk periods as condition of fund liberation	-reduce cost of fire prevention -reduce fire use in high risk periods	-smallholders supported by agrarian reform program	INCRA, MMA
PRONAF	-as above	-as above	-smallholders	MA, state governments
BNDES (PAI and FINAME)	-finance fire prevention and control methods and equipment -include clause that prohibits fire use for pasture management - application process includes fire risk of region (see Ch. 4)	-as above -reduce use of fire in pasture mgmt -lower priority for projects in regions of high fire risk (e.g. severe drought)	-medium and large landholders and firms -logging firms	BNDES
FINAM (for livestock and forestry projects)	-prioritize incentives to promote technological change (e.g. factories to produce lime or phosphorus fertilizer) -clause that prohibits fire use for pasture management -application process includes fire risk of region (Ch. 4)	-reduce cost of technologies that substitute fire use -reduce fire use as management tool -lower priority for projects in regions of high risk (severe drought)	-farmers and ranchers generally	SUDAM
PAGRI	-assist farm communities that wish to implement fire regulations, acquire fire-fighting equipment, and/or implement fire fighting practices	-encourage farm communities to create and implement fire regulations	-small holder farm communities	SUDAM, municipal governments
FRD	-fund municipalities that propose adoption of fire prevention and control plans	-encourage and disseminate fire management by local governments	-municipalities under the influence of CVRD	BNDES, municipal governments
Taxes (ICMS, IPI, II)	-exemption from taxes on purchases of fire prevention/control equipment for fire brigades and fire communities that are implementing fire regulations	-reduce cost of fire prevention/control equipment, encourage community fire regulations	-municipalities, communities and farm associations	State governments, Treasury, Internal revenue agency

sion of new frontier regions, these economic tools could be used to encourage agricultural intensification through agroforestry systems (Smith et al. 1998), cattle production intensification (Mattos and Uhl 1994), and forest management for timber (Barreto et al. 1998).

An initial step toward this policy integration was taken at the federal level through the creation of the National Council of the Legal Amazon (Conselho Nacional da Amazônia Legal, CONAMAZ), in 1995. CONAMAZ includes representatives of all federal ministries, and of the nine Amazon states, and is charged with the responsibility of formulating, accompanying through Congress, and helping to implement integrated federal policies for Amazonia. In practice, the Council's work thus far includes a survey of the programs and policies that apply to Amazonia (CONAMAZ 1998). An integrated approach to the region's policies that reflects the region's social and environmental concerns has yet to be internalized within the government. The fire problem represents an excellent opportunity to force such an integration, and to stimulate the debate on how best to reconcile the often divergent interests of economic development and the conservation of natural resources.

Fire risk warning systems

The vast ecological and economic damages caused by accidental fires in Amazonia may decline if the region's landholders use fire less—and invest in fire prevention more—when the risk of accidental fire is high. Currently, every landholder is on his own in deciding what this risk might be, even though the interest in fire risk is very high. In our encounters with farmers and ranchers, we are frequently asked "Is it going to be a dry year?" or "Should we invest in firebreaks this year?" The ability to predict the risk of accidental fire could help landholders decide when to burn their fields—if at all—and how much to invest in making firebreaks, contracting or training fire crews, and planning fire prevention strategies with neighboring landholders.

The ability to predict fire risk could also provide a powerful tool to government in its efforts to reduce the occurrence of accidental fire. The personnel, vehicles and other resources that are available to implement legislation designed to prevent accidental fire are tiny given the magnitude of the Amazonian agricultural frontier, and predictions of the severity of fire risk in different parts of Amazonia could help government agencies decide where to invest their scarce enforcement resources, and when additional resources are needed.

Early fire warning systems have been developed in several countries. The United States National Fire Danger Rating System (NFDRS) and the Canadian Fire Weather Index System (FWIS) combine data on weather, fuel characteristics in various ecosystem types, and fire behavior to generate fire risk indices that are updated daily (reviewed by Pyne et al. 1996). Millions of visitors at thousands of entrances to public lands in the United States, for example, encounter large signs with the latest color-coded fire risk assessment. Fines are levied on those who use fire in ways that are not permitted for the relevant risk level.

It will take a major investment in fire research for Brazil to develop a similar fire warning system for Amazonia. Both the US and Canadian fire warning systems are the fruit of decades of fire research and dozens of scientific careers that have yielded numerical models for the major fire-prone ecosystems, incorporating information on fire spread, fire energy release, ecosystem flammability, and human factors under a wide variety of climatic conditions.

In contrast, fire prediction is in its infancy in Amazonia. RisQue98 (Figure 4.2) is the first map that we are aware of that integrates data on rainfall, soils, and field measurements in Amazonian forests to identify fire-vulnerable areas. Its predictions are based on data from a mere 60 weather stations, compared to more than 1000 in the US! Many of the assumptions and algorithms used in the construction of RisQue98 must be verified in the field, and modified as new data arrive. Until a national fire research program is established within Brazil, fire prediction in Amazonia will depend upon models such as RisQue.

One promising approach to fire risk prediction in Amazonia would directly involve rural landholders. Farm communities and ranchers could calculate forest fire risk themselves once fire researchers have developed equations that describe the relationships between rainfall, soil water availability, and forest flammability for Amazonia's major forest and soil types. Fire risk prediction kits could be disseminated to rural landholders through rural extension programs, and would include rain gauges, rain data collection sheets, calculators and tools for sampling soil. Based on soil textural analysis, regional research centers would provide the appropriate equation for calculating forest fire risk, and extension agents would teach the landholders how to calculate fire risk with this equation using rainfall data as input. This approach to fire risk would address one of the most serious impediments to fire risk assessment in Amazonia, which is the insufficiency of rainfall data collection.

In the short term, an "El Niño early warning system" could act as an effective substitute for a comprehensive fire risk warning system. During most El Niño episodes, the surface temperatures of the southern Pacific Ocean begin to warm approximately six months prior to the onset of El Niño-related climate disruptions (such as Amazonian drought). Rapid dissemination of early El Niño signals would give Amazonian landholders time to incorporate the prospect of severe drought into their land management planning.

Emergency programs

In 1998, the Brazilian government took large strides in developing its capacity to respond to incipient periods of high forest fire risk. In a program involving IBAMA, INPE, the Brazilian army, the Brazilian Air Force, civil defense corps, fire-fighting brigades, and several other institutions, the Brazilian government responded to the prospect of a fiery dry season in 1998 by monitoring fires with satellite data, by sending fire fighting crews into areas of forest fire, and by prohibiting fire in counties of particularly high fire risk.

We are skeptical, however, of the capacity of government to substantially reduce fires in Amazonia through emergency plans that rely on troops moving into burning forests, or water dumped from aircraft. Tens of thousands of fires are ignited in Amazonia every dry season, and thousands of square kilometers of standing forests burn in hundreds of individual forest fire events that are effectively invisible to the government. There are simply not enough civil defense guards and fire fighters to put out thousands of kilometers of fire moving through the region's forests, especially considering that these fires are easily re-ignited by the smoldering logs on the forest floor that can continue to burn for weeks.

The central focus of any emergency plan to prevent and control forest fires during times of high risk must be Amazonia's rural landholders, for this is the only segment of Brazilian society that has sufficient labor, machinery, and presence across the vast Amazonian frontier to detect and suppress hundreds of widely distributed forest fires. Farmers contain forest fires by sweeping forest floor firebreaks free of organic debris fuel, and by monitoring these forests during subsequent weeks for the new fires that are inevitably ignited by smoldering logs. Large ranches usually have access to bulldozers, and can quickly scrape firebreaks in the path of fires in both pastures and forests. More importantly, rural producers from the poorest subsistence farmers to the wealthiest ranchers have an economic incentive to prevent and suppress forest fires because of the potential loss of the forests' subsistence and commercial value. From this perspective, the first step in preparing for years of forest fire emergencies—when vast tracts of forest are likely to become vulnerable to conflagrations—is to alert rural producers of the impending fire risk. Troops wielding hoses provide excellent television film footage, but can do little to reduce fire-related forest damage in the world's largest tropical forest.

6. Conclusion

Fire is deeply woven into the cultural and economic fabric of rural Amazonia. It is the basic tool by which subsistence farmers survive in remote forest regions, and it is the means by which larger landholders claim and defend their property, and prevent the regrowing forest from over-running their cattle pastures. In the absence of governmental capacity to implement fire-related legislation in the vast Amazonian frontier, strategies to reduce Amazonian burning must address the central role played by fire in the lives of Amazonian residents.

There is no quick mechanism for solving the Amazonian fire problem. In the long term, the solution will depend upon fundamental changes in the frontier setting—changes that reduce the rate of expansion of the frontier, stimulating an intensification of agricultural and forestry production systems in those regions that are already settled. A dramatic reduction in the availability of new forested land is needed to persuade Amazonian producers to use fire less, to invest more heavily in fire prevention, and to use and manage their natural resources more judiciously. Put another way, the extension of roads, waterways, and electric grids into remote forest lands is the best means of guaranteeing the continued presence of fire in agricultural landscapes, and the continued reckless use of natural resources generally.

We believe that there is some cause for optimism that the worst effects of burning can be reduced. Farmers and ranchers throughout the region suffer substantial economic losses through fires that escape their desired boundaries. Yes, fire is part of their cultural fabric, but rural Amazonians—more than anyone else—want a solution to the fire problem. The bitter irony is that most of these producers simply cannot afford to do without fire. If the "supply" of virgin forest land ripe for colonization increases at a slower rate, however, farmers and ranchers must turn to their existing land for sustenance and wealth, investing in fire-sensitive fences, fruit trees, and forage grasses that create a powerful incentive to use fire less. The prospect of slowing the growth of the frontier—or closing it completely—is a monumental task without precedent in the history of human civilization. There is little evidence in three decades of rapid Amazonian colonization that the trajectory of frontier expansion will provide an exception.

The challenge is to find more effective means to support rural landholders in their struggle to prevent and control unwanted fires, at least until such time as agricultural intensification reduces the incentive to burn. The common interest in a rural Amazonia that has less fire, less smoke, and lower risks to investments made in the land, is the seed of solutions for the Amazonian fire problem.

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Appendix I

The average number of hectares burned per year (mean (SE)), 1994-95, by property size and region, based on interviews of land-holders from five regions in the Brazilian Amazon.

	Type of Fire	Small (0-100 ha)		Medium (101-1000 ha)		Large (1001-5000 ha)		Very Large (>5000 ha)	
Five regions combined	Deforestation	2	(1.0)	9	(2.0)	63	(21.0)	190	(63.0)
	Forest surface fire	1	0.0	7	(4.0)	25	(12.0)	442	(268.0)
	Cleared land, intentional	6	(1.0)	29	(7.0)	76	(15.0)	292	(156.0)
	Cleared land, accidental	2	(1.0)	20	(6.0)	128	(40.0)	901	(506.0)
	Total	11	(2.0)	65	(12.0)	292	(56.0)	1.825	(842.0)
Northeast of Pará	Deforestation	1	(1.0)	7	(3.0)	23	(8.0)	390	(307.0)
	Forest surface fire	1	(1.0)	15	(11.0)	12	(10.0)	0	0.0
	Cleared land, intentional	8	(3.0)	31	(8.0)	136	(32.0)	404	(162.0)
	Cleared land, accidental	4	(3.0)	34	(13.0)	28	(16.0)	0	0.0
	Total	14	(4.0)	87	(24.0)	199	(42.0)	794	(305.0)
South of Pará	Deforestation	3	(2.0)	5	(3.0)	373	(301.0)	165	(149.0)
	Forest surface fire	1	(1.0)	12	(12.0)	0	0.0	1.295	(785.0)
	Cleared land, intentional	1	(1.0)	8	(8.0)	70	(39.0)	689	(464.0)
	Cleared land, accidental	2	(2.0)	52	(36.0)	352	(275.0)	2.700	(1452.0)
	Total	7	(4.0)	77	(55.0)	795	(538.0)	4.849	(2405.0)
Mato Grosso	Deforestation	2	(2.0)	15	(10.0)	81	(39.0)	7	(7.0)
	Forest surface fire	0	0.0	0	0.0	75	(45.0)	107	(107.0)
	Cleared land, intentional	1	(1.0)	14	(9.0)	66	(37.0)	0	0.0
	Cleared land, accidental	3	(1.0)	5	(4.0)	130	(80.0)	10	(9.0)
	Total	6	(2.0)	34	(17.0)	352	(129.0)	124	(105.0)
Rondônia	Deforestation	0	0.0	7	(5.0)	79	(18.0)	0	0.0
	Forest surface fire	1	(1.0)	1	(1.0)	0	0.0	0	0.0
	Cleared land, intentional	7	(2.0)	40	(26.0)	73	(23.0)	0	0.0
	Cleared land, accidental	2	(1.0)	2	(2.0)	0	0.0	0	0.0
	Total	10	(3.0)	50	(27.0)	152	(42.0)	0	0.0
Acre	Deforestation	3	(1.0)	12	(4.0)	33	(23.0)	336	(82.0)
	Forest surface fire	0	0.0	0	0.0	0	0.0	0	0.0
	Cleared land, intentional	9	(3.0)	28	(9.0)	14	(14.0)	20	(17.0)
	Cleared land, accidental	2	(1.0)	12	(5.0)	298	(134.0)	92	(89.0)
	Total	14	(3.0)	52	(11.0)	345	(136.0)	448	(127.0)

Appendix II:
Fire prevention and control techniques.

Firebreaks: In Amazonia, firebreaks are prepared either manually with the aid of a machete or hoe, or they are made by scraping away vegetation biomass down to the mineral soil using a bulldozer. It is about three times cheaper to make firebreaks using bulldozers (US$20/km with bulldozers vs. US$60/km manually), but the large capital investment that is needed to purchase bulldozers makes them inaccessible to most rural small holders. Firebreaks are much more costly when tree trunks must be cut, such as is the case around recently felled forest. The second cost of firebreak preparation is the lost grazing or agricultural production on the strip of land from which vegetation is removed. For example, two kilometers of firebreak that is 5 meters wide destroys one hectare of pasture grass, reducing cattle production profits.

Around pastures, felled forests and tree plantations: Firebreaks should be placed around the perimeter of agricultural areas both to defend these areas from accidental burning, and to contain the fires that might be ignited in these areas either intentionally or accidentally. Firebreaks along upwind boundaries and along roads and cattle pastures are necessary to defend the area from fire on neighboring land. Firebreaks along downwind boundaries, and other boundaries where neighboring lands could be damaged by accidental fire, are needed to defend neighboring lands from fire damage. Fires around pastures should be made on either side of fencing to protect this valuable investment from fire damage.

The width of the firebreak that is appropriate varies depending upon wind conditions, and upon the structure of the neighboring vegetation, and is an important area of research. On cleared lands, where winds are strong, firebreaks of ten meters width or more may be necessary to prevent fire from jumping into the area that is being defended. A second firebreak 30 to 50 m downwind reduces the risk that fires which jump the first firebreak will enter the protected area. Similarly, much larger firebreaks of 20 to 30 m width can be prepared in pastures by burning off the vegetation between two parallel firebreaks. The risk that these intentional fires will escape into the rest of the pasture can be reduced by igniting these fires as "back burns" along the downwind edge of the vegetation strip, and by burning late in the afternoon, as declining temperatures and increasing air humidity reduce the intensity of the fire.

Tall, woody vegetation sends flaming embers into the air as it burns and therefore easily jumps across firebreaks. Wide firebreaks and vigilance in the case of an approaching fire, to quickly extinguish embers that fall into the protected vegetation, are needed to defend agricultural systems from fires in tall, flammable vegetation such as secondary forest.

Forests: Firebreaks can be made around the outer perimeter of forests to protect them from accidental fire. A second firebreak can be made ten to twenty meters into the forest interior at little expense by sweeping a one-meter-wide trail free of organic debris using brooms or rakes. This narrow strip is effective in stopping fires that jump the firebreak along the forest perimeter because fires quickly diminish in size when they move into the forest. To be most effective, fallen tree trunks that lie across the strip should be cut to prevent the trunks from transmitting fire deeper into the forest.

Firebreaks in the forest interior can also be made by bulldozing a swathe through the forest. The disadvantage of this technique is that it allows a flammable strip of vegetation to grow which can, itself, become a line along which fire is transmitted.

Firebreaks in the forest interior are particularly important when the neighboring vegetation has standing dead trees which could ignite and fall across the perimeter firebreak.

Fuelbreaks: Strips of vegetation that are difficult to ignite serve a similar purpose to firebreaks in defending areas from accidental fire. Primary forests are the least flammable vegetation type in Amazonia, and currently act as giant fuelbreaks across agricultural landscapes, greatly reducing the risk of accidental fire. Currently, however, the location of primary forests is determined mostly as an outcome of the decision-making process to identify the location of cattle pastures and crop fields that are most profitable. Forests are also cleared along roads before they are cleared elsewhere on the property to reduce the risk of land invasion by squatters, and to demonstrate "productive use" of the land (which is a criterion for retaining land possession). Hence, the potential of forests to protect properties from fires started along roadsides is generally not realized because of competing concerns for maintaining control of land.

The minimum width of primary forest that is necessary to provide an effective fuelbreak has not been studied, but varies depending upon prevailing wind direction and forest type. The fuel layer of forests dries more quickly near edges, where warm, dry air from neighboring non-forest vegetation and greater light penetration into the forest speed drying of the litter layer. Fuelbreaks must be wide enough to maintain a core area that is beyond this zone of drying. Kapos (1989) and

Kapos et al. (1993) measured drier, warmer air up to 60 meters into the downwind edge of a forest near Manaus, and Uhl and Buschbacher (1985) documented fire penetration into forest edges of up to 200 meters. A second consideration in the use of forest fuelbreaks is the deterioration of the forest edge that occurs over time. Tree mortality is high along forest boundaries with non-forest vegetation (Laurance et al. 1997). A one-kilometer forest strip is recommended by Holdsworth and Uhl (1997), which may be impractical because of the large amount of land (and forest) that is removed from production.

Other types of fuelbreaks can be planted using trees or shrubs with leaves that are difficult to ignite. This is a promising area of research for Amazonian fire management.

Backburns ("contra-fogo"): When pastures or felled forests are intentionally burned, the risk that these fires escape into neighboring ecosystem can be reduced by igniting "backburns". These fires are ignited along the interior edge of the firebreak that bounds the area along its downwind edges, and they burn slowly into the wind, consuming available fuels and broadening the width of the down-wind firebreak. Landholders can reduce the cost of preparing firebreaks along the downwind border using backburns, since the firebreaks that are needed to contain a backburn can be much narrower than the firebreaks necessary to contain the much larger fires that move in the direction of the wind. Hence, backburns can be used to substantially reduce the costs of firebreak preparation.

Backburns are most effective if they are set quickly along the entire down-wind edge, which is facilitated by a hand-held "drip torch", which drips flaming kerosene along the firebreak edge. Back burns require more labor on the day of the burn than do intentional fires set without back burns, because at least one person must ignite the back burn, and at least one other person should watch the back burn to make sure that it is not blown back over the firebreak. In the absence of a firebreak, back burns can be set along the down wind boundary as long as a team of people follows close behind the person setting the fire to extinguish the down wind fire front with tarps or water.

Pasture fuel management: The risk of fire in pastures can also be diminished by increasing grazing pressure in those pasture areas that are most vulnerable to sources of ignition. Heavy grazing reduces the amount of fuel that is available to burn, and can even make pastures resistant to fire if individual clumps of grass are separated by soil with little or no organic matter on it. The disadvantage of this practice is that intensive grazing pressure can allow weed species to invade the pasture. Another disadvantage of this technique is the added investment in fencing that is required to make smaller paddocks that are necessary to manage cattle herd grazing rotations more intensively.

Surveillance and communication: One of the critical ingredients of fire prevention in Amazonia is close surveillance of neighboring lands for approaching fires. When smoke plumes are detected streaming up into the air, family members, friends, neighbors, and employees can be summoned to help defend the property boundary from approaching fires, or extinguish the fire. "Fire spotters" posted in fire watch towers can see approaching fires before people working on the ground. Communication with neighboring landholders is the best way to learn when intentional fires will be set on neighboring land. Neighbors can also agree to invite each other to accompany intentional burns, and to notify each other in the event of an accidental burn spotted.

Cool burns: The risk of accidental fire can also be reduced by setting intentional fires only at times when high fuel moisture contents, low air temperatures, or high air relative humidity reduce the energy of the fire, making it easier to control. Fires can be kept "cool" by burning shortly after rain events, before fuel moisture contents become very low. Felled forests that are burned within the first one to two months of the dry season have higher moisture contents and lower fire energy than they do four months into the dry season, and produce fewer embers that can ignite neighboring lands. Landholders should burn pastures for weed control only within three to five days of the last rain event of at least one centimeter, when forage moisture content is still high and fire energy is therefore quite low.

There is a very large cost of cool burning, however, which is the reduced efficacy of the burn in converting the felled forest into nutrient-rich ash, or in killing undesired woody plants that are invading cattle pastures: low-energy fires do not perform these functions as well as high-energy fires. For example, slash and burn farmers of the Rio Capim region, near Paragominas, were able to use only 70% of the land they prepared through forest felling and burning because the rest did not catch fire or was covered by large tree trunks. The amount of recently-felled forest biomass that is consumed by a cool fire can be increased if farmers carefully inspect each tree that is cut down to make sure that the felled stem is completely severed from the stump. Strips of bark or wood can conduct water into the fallen stem, preventing it from drying and reducing fuel consumption during burning.[22]

The temperature of fires can also be kept low by burning during cool, moist hours of the day. Fire temperatures are hottest in the early af-

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[22] *C. Perreira, unpublished data.*

ternoon, from 13:00 to 14:00 h, when air temperature is high, and air relative humidity is low. Fire temperatures drop precipitously late in the afternoon as the sun goes down and wind-speeds slow, and can even be extinguished as the air continues to cool into the evening. Landholders should ignite their felled forests and weedy pastures as late in the afternoon as is possible without limiting the fire's desired effects.

Planning for fire: The most important step in successfully suppressing fire must be taken before the fire is even ignited. Landholders must analyze the risk of accidental fire on their land and develop a plan for suppressing fire should it occur. This plan should evaluate the best way to combat fires should they jump firebreaks, identifying the most favorable locations for bulldozing emergency firebreaks and back burns, and designing the procedures that should be taken if a bulldozer is not available. The plan should foresee the labor needs that would be required in the case of accidental fire, and should involve training of farm/ranch personnel in fire-fighting techniques and in plan implementation. The areas at risk should be prepared to implement the plan as well. If a water tank or bulldozer is available, is there adequate access to the areas of burn risk? Are there gates in the fences, logs blocking roads or trails? Is there a source of water for filling the tank? The plan should also be discussed with neighboring landholders, and agreements made so that equipment and personnel are shared in the event of an accidental fire on either property.

Pasture fires: Pastures with abundant forage grass burn hot and fast, and are difficult to extinguish. The landholder must accept the fact that an area of pasture will burn, and that the fire will only go out when it runs out of fuel. The challenge is to surround the pasture with firebreaks as soon as possible, without running the risk that the fire will jump over the breaks. Accidental pasture fires can be suppressed by quickly bulldozing a new firebreak downwind and setting a back burn (if a bulldozer is available!). In the absence of heavy machinery, the most effective tool for fighting pasture fire is often back burning without a firebreak. One person igniting the back burn, and two or three people following close behind to extinguish the fire along the downwind edge of the burn, are usually adequate to set a back burn, unless the pasture has not been grazed in several weeks and has abundant fuel. Fire smotherers, portable back-pack water pumps, machetes and hoes are important tools in igniting a back burn without a firebreak.

If portable water tanks are available, pasture fires can sometimes be stopped or slowed down by spraying the pasture vegetation that lies downwind from the fire.

Water-carrying helicopters can extinguish accidental pasture fires, but only if the fires are localized and there is a nearby source of surface water. Many pasture fires extend along fronts that can be kilometers in length and would be difficult to extinguish with water poured from the sky. Moreover, water-carrying helicopters cost ~ $6,000,000 each, and would never be available in sufficient number to combat the tens of thousands of fires that stretch along Amazonia's 2,000-km arc of deforestation.

Forest fires: Fires that invade forests can also be combated by circumscribing them with firebreaks. Since forest fires are usually "cool", with low flame heights and low speeds, a narrow (one-meter wide) strip is usually sufficient as a firebreak. Brooms and rakes can be quickly assembled by tying branches together, and used to sweep the leaf litter from the soil along the strip. The strip is most effective if it is placed in the deepest shade of the forest, where the high relative humidity will help further suppress the fire.

One of the most difficult aspects of forest fire suppression is the ignition of tree trunks that are lying on the ground, for once ignited they are difficult to extinguish and can burn for several weeks. Burning tree trunks may have no external flames during evening and nighttime, when air dampness increases, but spring into flame the subsequent morning. Since forest fire triggers the rapid shedding of leaves from forest trees and lianas, forests can burn repeatedly when the flames and sparks of burning trunks ignite the layer of recently-shed leaves.[23] For this reason, forest fires that have been extinguished must be visited daily to see if fires have ignited again. Low-income farmers across Amazonia, who depend upon forests for a variety of subsistence products, suppress the fires that burn their forests by surrounding them with strips, cutting through trunks that lie across these strips, then watching the forest thereafter for signs of new smoke curling up through the forest canopy—signaling a new round of forest floor sweeping.

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[23] *M. Cochrane, personal observation.*

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Conservation and Development of Brazil's Tropical Forest Regions is a publication series produced jointly by the World Bank and the Secretariat for the Coordination of Amazon Affairs. The series consists of 100 - to 200- page books, amply illustrated and written in jargon-free language (English and Portuguese), which provide state-of-the-art synthesis of issues relevant to the Pilot Program in particular, and to tropical forest conservation and development in general. In addition to the current volume on forest fires, future volumes will address issues such as logging, demarcation and sustainable use of indigenous lands, and strategies for biodiversity protection and use. The series is aimed to raise awareness of such issues among a broad audience in Brazil and internationally.

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