TROPICAL FOREST COMMUNITY ECOLOGY

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To my parents Walter and Alice Carson: thank you for years of unconditional love and support, and to my son Chris Carson: you have changed the way I see the forest.

Walter P. Carson

Chapter 27

ENVIRONMENTAL PROMISE AND PERIL IN THE AMAZON

William F. Laurance

OVERVIEW

The Amazon basin sustains about half of the world's remaining tropical forests, and is being destroyed and degraded at alarming rates. About one fifth of the Amazon has been deforested and perhaps another third degraded by selective logging, surface fires, habitat fragmentation, and edge effects. Hunting and illegal gold mining have also altered large expanses of the region, even in many remote areas. The rapid pace of forest conversion may accelerate in the near future because of a major planned expansion of transportation infrastructure, which greatly facilitates forest colonization, predatory logging, and land speculation. If such projects continue unabated, much of the basin's forests could be fragmented on a large spatial scale, sharply increasing the vulnerability of surviving forest tracts to a range of exploitative activities.

However, the conservation prognosis is not entirely negative. In parts of the Amazon, regenerating forest on abandoned land provides habitat for certain wildlife and is far superior to cattle pastures in its hydrological functions and carbon storage. The greatest cause for optimism is the prospect of a substantial expansion of protected and semi-protected areas, particularly in Brazilian Amazonia. In addition, a growing network of indigenous lands is helping to reduce forest exploitation in some areas. Unfortunately, many reserves are poorly managed and protected, and a key challenge is to establish basic staffing and infrastructure for planned and existing parks. Improving the enforcement of environmental legislation in remote frontier areas is also a daunting challenge for Amazonian nations.

INTRODUCTION

In the biblical book of Revelation, the dawning of the Apocalypse sees four dark horsemen – famine, war, pestilence, and disease – raining down horror on humanity. Some believe that the Amazon could face its own kind of apocalypse in the coming century. Its horsemen will be different: not famine but the rapid expansion of agriculture; not war but industrial logging; not pestilence but wildfires; and not disease but widespread forest fragmentation. Others, however, believe that the analogy of an apocalypse is too pessimistic (e.g., see Putz and Zuidema Chapter 28, this volume). In this chapter I briefly describe the most important threats to the Amazon, and suggest how the basin's forests might be altered in coming decades. The Amazon, I conclude, faces a dynamic combination of environmental promise and peril.

The Amazon basin sustains well over half of the world's remaining tropical rainforest (Whitmore 1997) and includes some of the most biologically rich ecosystems ever encountered. Closed-canopy forests in the basin encompass about 5.3 million km^2, an area the size of western Europe (Sarre *et al.* 1996). By far the most extensive forest type is *terra firme* – forests that are not seasonally flooded. There also are large areas of seasonally flooded forest along rivers and in floodplains (termed *várzea* if they are flooded by relatively nutrient-rich white waters, and *igapó* if inundated by nutrient-poor black waters), and limited areas of bamboo forest and vine forest. In addition, scattered savannas and open forests occur in drier areas of the basin, where narrow

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PREFACE

It is not hyperbole to say that there has been an explosion of research on tropical forest ecology over the past few decades. The establishment of large forest dynamics plots in tropical forests worldwide, in and of itself, has led to a near revolution in our understanding of forest change. In addition, there has been a substantial increase in the use of models and experiments to test long-standing theories developed to explain the striking patterns found in tropical forests and the putative mechanisms that underlie these patterns. When we started this project, we felt that a comprehensive synthesis of tropical forest community ecology was necessary in order to help the field move forward. Of course, no single volume could do this. Nonetheless, this book is our attempt to make a significant contribution to the field, and to ask anew: What are the main theories in tropical ecology, and which ones are supported or refuted by empirical data? Thus, we have attempted to assemble a volume that describes the most up-to-date findings on the important theories of tropical forest community ecology. We hope that this book accomplishes this goal to the degree possible, while at the same time providing a road map of what we know, what we think we know, and where future research is most needed.

The focus of the chapters in the volume is at the community level because this is where some of the most fundamental questions in tropical ecology exist. Indeed, perhaps the greatest challenge to community ecologist is to explain what processes account for the maintenance of the staggering diversity of plants and animals common in tropical forests around the globe. Still, our emphasis on communities definitely reflects our bias as community ecologists. While we have focused on communities, we certainly recognize the important contributions to tropical ecology that have come from those who study different levels of ecological organization. Indeed, it is difficult to understand communities without understanding the ecology of populations and individuals. We decided to focus on forest communities because, to date, that is where the bulk of research on tropical community ecology has been conducted. We acknowledge that our focus has forced us to omit many important studies. Nonetheless, the emphasis on tropical forest community ecology provides enough material to fill multiple edited volumes, and thus we have attempted to focus on the areas that have received the most empirical attention, along with some topics that are currently nascent, but are rapidly becoming key areas in tropical ecology.

Each chapter in this book was reviewed by at least two relevant experts. We thank these reviewers for their efforts and we are indebted to all of them. We will not list them by name, thus allowing them to remain anonymous. We also thank the production team at Newgen Imaging Systems, and our editors at Blackwell for guiding us through the publication process.

This book, as with all edited volumes, would not have been possible without the dedicated contributions of the authors, each of whom is an expert in his or her respective area of study. For their hard work, truly top-notch contributions, and their patience throughout this process, we owe them a great deal of gratitude. This book is a tribute to their research, along with the research of all of the other scientists whose work is cited in this volume.

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FOREWORD

The present volume captures the excitement generated by an explosion in tropical forest research. When I was a graduate student in the late 1970s, it seemed to be possible to read every new article published on tropical forests. The ISI Web of Science© confirms this schoolboy memory. Just 289 articles published between 1975 and 1979 included the words "forest*" (for forest, forested or forests) and the name of a tropical country (or tropic*) in their titles. By reading just one or two articles a week, I was able to keep abreast of the entire literature on tropical forests. This would be nearly impossible today. Between 2002 and 2006, 2593 articles met the criteria described above reflecting a nine-fold increase in the rate of publication of tropical forest articles since the late 1970s. This explosion has been driven by new discovery; new theory; new technology; new challenges posed by global change, deforestation and other threats to tropical biodiversity; and ongoing interest in theory posed in the 1970s and earlier. This volume illustrates each of these developments.

In the 1970s, we all "knew" that ants were predatory with the exception of an insignificant few observed at extrafloral nectaries. No one guessed that plant exudates supported most of the great biomass of ants (Chapter 6). Likewise, no one guessed that plants consisted of a mosaic of plant plus endophytic fungi and that the endophytic fungi were hyperdiverse with tens to hundreds of species inhabiting each leaf in the forest (Chapter 15). The roles of herbivorous ants and endophytic fungi are only beginning to be explored, and their implications for forest biology are potentially profound. New theories of chance, dispersal and seed limitation (Chapters 2, 8 and 14) and new tradeoffs postulated between fecundity and habitat tolerance (Chapter 11) also hold the potential to change our understanding of how tropical forest communities are structured and are only now beginning to be explored.

In the 1970s, we would have been mystified by functional (Chapter 10) and phylogenetic (Chapter 20) approaches to plant community ecology and the knowledge base in physiology, morphology and molecular genetics that makes these approaches possible today. Both approaches have the potential to reduce the immense number of species of tropical forest plants to a manageable number of ecologically distinct groups or crucial relationships among species' traits. Today, we are striving to bring functional, phylogenetic and ecological approaches together for 6000 plus tropical tree species found in the network of large Forest Dynamics Plots maintained by the Center for Tropical Forest Science (Chapter 7).

A graduate student in the late 1970s would have been familiar with the plant favorableness (Chapters 3 and 4), regeneration niche (Chapter 6), Janzen–Connell (Chapter 13) and bottom-up versus top-down hypotheses (Chapters 16–19 and 21) addressed by one third of the chapters in this volume and would be delighted to read the progress summarized here. I was also familiar with the potential of large forest plots – Robin Foster and Steve Hubbell were busy generating excitement for a grand new plot when I was a graduate student on Barro Colorado Island – and it is also a delight to see that potential realized (Chapter 7). Likewise, Phyllis Coley and I were contemporaries as graduate students on BCI as she revolutionized the study of herbivory (and I muddled about with island communities of birds and lizards), and it is a delight to see many of her ideas extended to a new framework to explain herbivory gradients across tropical rainfall gradients (Chapter 5) and to bioprospecting for new pharmaceuticals (Chapter 25).

The final section of this volume (Chapters 22–28) would shock a 1970s graduate student. A potential tropical deforestation crisis was only first publicized in the early 1970s (Gómez-Pompa *et al.* 1972 *Science* 177, 762–765). The severity of deforestation in 2007 and the many exacerbating problems (Chapters 24, 26 and 27) would be entirely unexpected. The potential for solutions through natural secondary succession on abandoned agricultural land (Chapters 22 and 23) and conservation action (Chapter 25) proposed, in some cases, by my peers from the late 1970s on BCI would be equally surprising and heartening.

Where do we go from here? What might a graduate student do in 2007 to have the greatest future impact? There are many answers. Spectacular new data sets are being made available by the Angiosperm Phylogeny Group, by several new efforts to assemble global plant and animal trait data, and by the new remote sensing technologies mobilized in global change research. Those trained to capitalize on these and other similar data sets will make many important contributions.

Simultaneously, we are still in the age of discovery in tropical forest ecology. No one suspected that there might be millions of species of endophytic fungi in tropical leaves until Elizabeth Arnold looked starting in 1996. We are equally ignorant of the roles of myriad other organisms. Even the local point diversity of herbivorous insects remains an unknown. Basic discovery will continue to make many crucial contributions to tropical forest ecology.

Finally, I will return to the nine-fold explosion in tropical forest publication rates mentioned in the first paragraph. The publication rate for extra-tropical forests increased just 4.3-fold over the same time interval. This latitudinal difference has been driven by a 15-fold increase in publication rates for authors from tropical countries. The increase in tropical forest publication rates falls to 5.8-fold when authors with tropical addresses and unknown addresses are excluded. The rapid increase in publication rates for authors from tropical countries is very uneven. Scientists from Brazilian and Mexican institutions increased their rate of tropical forest publications by 71-fold between 1975–1979 and 2002–2006 (from just 9 to 644 articles). Perhaps not surprisingly the authors of this volume include one Brazilian (Chapter 21) and two Mexicans (Chapter 5). Increasingly, scientists from Brazil, Mexico, and other tropical countries will formulate the tropical forest research agenda and determine what research has the greatest future impact. This is a positive development.

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strips of rainforest vegetation (termed "gallery forest") often persist along permanent rivers and streams (IBGE 1997).

Most of the Amazon is flat or undulating, at low elevation (<300 m), and overlays very poor soils. Roughly four-fifths of the Amazon's soils are classified as latosols (Brown 1987, Sarre *et al.* 1996), which are heavily weathered, acidic, high in toxic aluminum, and poor in nutrients (Richter and Babbar 1991). Somewhat more productive soils in the Amazon are concentrated along the basin's western margin, in the Andean foothills and their adjoining floodplains. These areas are much more recent geologically than the rest of the basin and thus their soils are less heavily weathered.

Rainfall varies markedly across the Amazon. In general, forests in the basin's eastern and southern portions are driest, with the strongest dry season. Although evergreen, these forests are near the physiological limits of tropical rainforest, and can persist only as a result of having deep root systems that access groundwater during the dry season (Nepstad *et al.* 1994). The wettest and least seasonal forests are in the northwestern Amazon, with the central Amazon being intermediate; forests in these areas do not require deep roots.

DIRECT THREATS TO THE AMAZON

Agriculture

Historically, Amazonian development has been limited by the basin's poor soils, remoteness from major population centers, and diseases such as malaria and yellow fever. This is rapidly changing. In the Brazilian Amazon, which comprises two-thirds of the basin, more forest was destroyed during the last 30 years than in the previous 450 years since European colonization (Lovejoy 1999). Losses of Amazonian forests in Bolivia, Ecuador, Colombia, and Peru have also risen substantially in recent decades (e.g., Sarre *et al.* 1996, Viña and Cavalier 1999, Steininger *et al.* 2001a,b).

Deforestation rates in the Amazon average roughly 3–4 million ha per year – an area larger than Belgium. The most reliable deforestation statistics are for the Brazilian Amazon (Figure 27.1). These statistics have been produced annually since 1989 (except 1993) by Brazil's national space agency based on interpretation of satellite imagery (INPE 2005). Despite various initiatives to slow forest loss, deforestation in Brazilian Amazonia has accelerated substantially since 1990 ($F_{1,14} = 11.17$, $R^2 = 44.4\%$, $P = 0.005$; linear regression with log-transformed deforestation data). Considerable year-to-year variation in deforestation rates (Figure 27.1) results from changing economic trends (such as fluctuating commodity prices and international currency-exchange rates, which affect timber, beef, and soy exports); evolving government policies (such as stabilization of Brazilian hyperinflation in 1994 that freed pent-up funds for development, ongoing infrastructure expansion, periodic crackdowns on illegal logging, and the designation of new protected areas); and climatic conditions (particularly droughts, which strongly influence forest burning) (Laurance 2005a). Rates of deforestation have been especially high in recent years; from 2002 to 2004, nearly 2.5 million ha of forest was destroyed annually – equivalent to 11 football fields a minute. This increase mostly resulted from rapid destruction of seasonal forest types in the southern and eastern parts of the basin; relative to preceding years (1990–2001), forest loss shot up by 48% in the states of Pará, Rondônia, Mato Grosso, and Acre (Laurance *et al.* 2004a).

The most important proximate drivers of deforestation in the Amazon today are directly related to agriculture. The greatest cause of forest loss is large-scale cattle ranching, typically by relatively wealthy landowners. Ranchers commonly use bulldozers to extract timber prior to felling and burning the forest (Uhl and Buschbacher 1985). Large- and medium-scale ranchers may cause as much as three-quarters of all deforestation in the Brazilian Amazon (Fearnside 1993, Nepstad *et al.* 1999a) and also account for much forest loss elsewhere in Latin America (e.g., Viña and Cavalier 1999). From 1990 to 2005, the number of cattle in Brazilian Amazonia nearly tripled, from about 22 million to 60 million head. Brazilian beef exports rose sharply during this period both because of favorable exchange rates

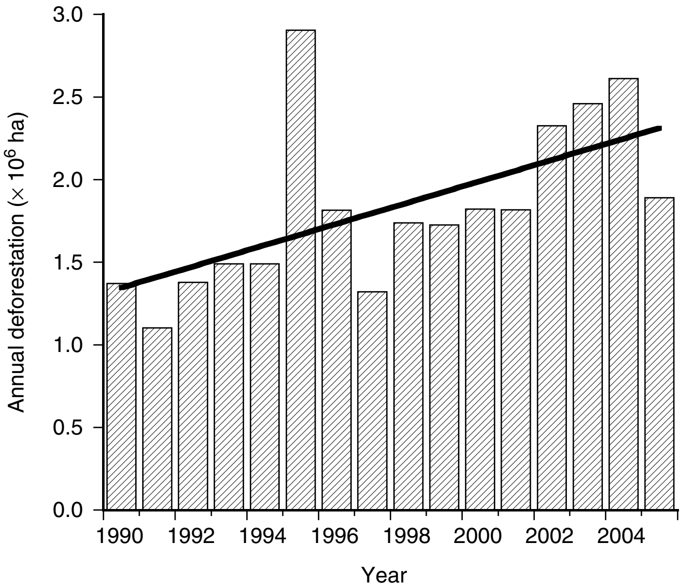

Figure 27.1 Estimated deforestation rates in Brazilian Amazonia from 1990 to 2005 (data from INPE 2005). The regression line shows the overall trend.

and because Brazil is free from hoof-and-mouth disease (Kaimowitz *et al.* 2004, Laurance 2005a).

Second in importance is slash-and-burn farming by landowners who clear small (typically 1–2 ha) areas of forest each year to plant manioc, corn, bananas, and other crops (Fearnside 1993). The forest's understory is slashed with machetes and the debris is ignited during the dry season. The ash from the burned vegetation provides a pulse of plant nutrients, which supports crops for a few years before the area is left to fallow and the farmer is forced to clear more forest. Slash-and-burn farming occurs both opportunistically (often illegally) and as a result of government-sponsored colonization programs that allocate small forest tracts (usually <100 ha) to individual families. Brazil has hundreds of Amazonian colonization projects involving at least half a million people (Homma *et al.* 1992), initiated in part to help divert population flows that would otherwise further overcrowd Brazil's major cities (Fearnside 1990, 1993).

The third cause of deforestation, industrial agriculture, is growing rapidly in importance in drier areas of the Amazon basin and in adjoining transitional forests and *cerrado* woodlands and savannas. Most of these farms are devoted to soy, which involves clearing large expanses of relatively flat land for crop production. Soy farming has been a major cause of deforestation in northern and eastern Bolivia (Steininger *et al.* 2001a,b) and is rapidly increasing in Pará, Maranhão, and especially Mato Grosso states in Brazil (Fearnside 2001). In 2004 nearly half of all deforestation in Brazilian Amazonia occurred in Mato Grosso (INPE 2005), largely as a result of the explosive growth of industrial soy farms (Laurance *et al.* 2004a).

Logging

In recent decades, industrial logging (Figure 27.2) has increased sharply in the Amazon, and now affects 1–2 million ha of forest each year in Brazilian Amazonia alone (Nepstad *et al.* 1999b, Asner *et al.* 2005). In the tropics, logging is normally selective, in that only a relatively small

Figure 27.2 Industrial logging, like this operation in northern Bolivia, creates labyrinths of roads that promote forest colonization and overhunting (photograph by W.F. Laurance).

percentage of all trees are harvested. However, the number of harvested species varies considerably among regions. In new frontiers, only 5–15 species are typically harvested (1–3 trees ha^{-1}), but in older frontiers up to 100–150 species are harvested (5–10 trees ha^{-1}) (Uhl *et al.* 1997). Valuable timbers such as mahogany (*Swietenia* spp.) are overexploited and play a key role in making logging operations profitable (Fearnside 1997).

The immediate impacts of logging mostly arise from the extensive networks of roads, tracks, and small clearings created during cutting operations (Figure 27.2), which cause collateral tree mortality, soil erosion and compaction, vine and grass invasions, and microclimatic changes associated with disruption of the forest canopy (Uhl and Vieira 1989, Veríssimo *et al.* 1992, 1995, Johns 1997). Many sensitive wildlife species decline in logged forests (Johns 1997 and references therein). In addition, logging has important indirect effects; by creating labyrinths of forest roads, logging opens up areas for colonization by migrant settlers and ranchers who often use destructive slash-and-burn farming methods (Uhl and Buschbacher 1985, Veríssimo *et al.* 1995). Logging often leads to an increase in hunting, which can seriously affect some wildlife species. In the Malaysian state of Sarawak, for example, a single large logging camp was estimated to consume over 30,000 kg of wildlife meat each year (Bennett and Gumal 2001).

Logging is a multi-billion dollar business in the Amazon. Brazil currently has about 400 domestic timber companies operating in the Amazon, which operate from 6000 to 7000 timber mills, whereas Bolivia has about 150 domestic companies (Laurance 1998). In addition, multinational timber corporations from Malaysia, Indonesia, China, South Korea, and other Asian nations have moved rapidly into the Brazilian Amazon by acquiring control of large forest tracts, often by purchasing interests in local timber firms. In Guyana, Suriname, and Bolivia, these corporations have obtained extensive long-term forest leases (termed "concessions"; Colchester 1994, Sizer and Rice 1995). In 1996 alone, Asian corporations invested more than 500 million dollars in the Brazilian timber industry (Muggiati and Gondim 1996). Asian multinationals now own or control at least 13 million ha of Amazonian forest (Laurance 1998).

A striking feature of the Amazonian timber industry is that illegal logging is rampant. A 1997 study by Brazil's national security agency concluded that 80% of Amazonian logging was illegal, and recent raids have netted massive stocks of stolen timber (Abramovitz 1998). Aside from widespread illegal cutting, most legal operations from the hundreds of domestic timber companies in the Amazon are poorly managed. A government inspection of 34 operations in Paragominas, Brazil, for example, concluded that "the results were a disaster," and that not one was using accepted practices to limit forest damage (Walker 1996). In the late 1990s, in a controversial attempt to gain better control over Amazonian logging operations, Brazil opened 39 of its National Forests, totaling 14 million ha, to logging, arguing that concessions would not be granted to companies with poor environmental records (Anon. 1997). Brazil plans greatly to expand its system of National Forests in the Amazon, adding 50 million ha of new logging reserves by the year 2010 (Veríssimo *et al.* 2002).

Forest fragmentation

The rapid pace of deforestation is causing forest fragmentation on many spatial scales. On a basin-wide scale, major new highways, roads, and transportation projects are now penetrating deep into the heart of the basin, promoting forest colonization, logging, mining, and deforestation in areas once considered too remote for development (Laurance 1998, 2005a, Carvalho *et al.* 2001, Laurance *et al.* 2001a,b, 2002a, 2004a). By 1988, the area of forest in Brazilian Amazonia that was fragmented (<100 km^2 in area) or prone to edge effects (<1 km from forest edge) was more than 150% larger than the area that had actually been deforested (Skole and Tucker 1993). Because over 18% of the region's forests have now been cleared (INPE 2005), the total area affected by fragmentation, deforestation, and edge effects could constitute one third or more of the Brazilian Amazon today (Laurance 1998).

On a landscape scale, different land uses tend to generate distinctive patterns of fragmentation. Cattle ranchers destroy large, rectangular blocks of forest, and habitat fragments in such landscapes are often moderately regular in shape (Figure 27.3, right). Forest-colonization projects, however, result in more complex patterns of fragmentation (Figure 27.3, left), creating very irregularly shaped fragments with a high proportion of forest edge (Dale and Pearson 1997, Laurance *et al.* 1998b). Remote-sensing studies suggest that, as a result of rapid habitat fragmentation, nearly 20,000 km of new forest edge is being created each year in the Brazilian Amazon (W. Chomentowski, D. Skole, and M. Cochrane personal communication).

Habitat fragmentation has myriad effects on Amazonian forests (reviewed in Laurance *et al.* 2002b), such as altering the diversity and composition of fragment biota, and changing ecological processes like pollination, nutrient cycling, and carbon storage (Lovejoy *et al.* 1986, Bierregaard *et al.* 1992, Didham *et al.* 1996, Laurance and Bierregaard 1997). Edge effects – ecological changes associated with the abrupt, artificial edges of forest fragments – penetrate at least 300 m into Amazonian forests (Figure 27.4; Laurance *et al.* 1997, 1998a, 2000, 2002b). Moreover, forest fragmentation appears to interact synergistically with ecological changes such as hunting, fires, and logging (Laurance and Cochrane 2001, Peres 2001, Cochrane and Laurance 2002, Laurance and Peres 2006), collectively posing an even greater threat to the rainforest biota.

As a result of such changes, many faunal groups, including insectivorous understory birds, most primates, and larger mammals,

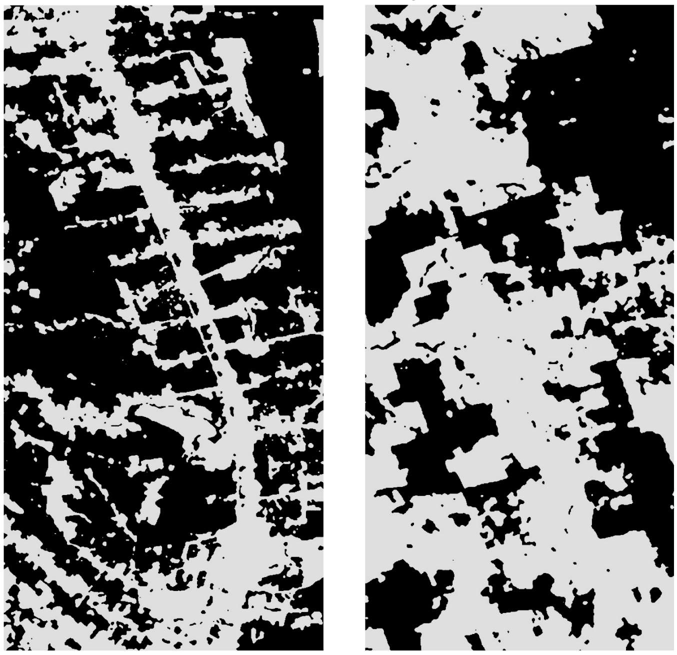

Figure 27.3 Different land uses in the Brazilian Amazon produce distinctive patterns of forest fragmentation. Government-sponsored colonization projects in Tailândia result in a "fishbone" pattern of fragmentation, which differs from the fragmentation pattern caused by cattle ranching near Paragominas. Each image shows an area of about 600 km^2.

decline in abundance or disappear in fragmented forests (Lovejoy *et al.* 1986, Schwartzkopf and Rylands 1989, Bierregaard *et al.* 1992, Stouffer and Bierregaard 1995). Numerous invertebrate species, such as certain ants, beetles, butterflies, and termites, also respond negatively to fragmentation and edge effects (Klein 1989, Didham *et al.* 1996, Brown and Hutchings 1997, Carvalho and Vasconcelos 1999). Remarkably, many arboreal mammals, understory birds, and invertebrates are unable or unwilling to cross even small (30–80 m wide) forest clearings (Laurance *et al.* 2002b, Laurance, S.G. *et al.* 2004).

Wildfires

Under natural conditions, large-scale fires are evidently very rare in Amazonian rainforests, perhaps occurring only once or twice every thousand years during exceptionally severe El Niño droughts (Sanford *et al.* 1985, Saldariagga and West 1986, Meggers 1994, Piperno and Becker 1996). Closed-canopy tropical forests are poorly adapted to fire (Uhl and Kauffman 1990), and even light ground-fires kill many trees and virtually all vines (Kauffman 1991, Barbosa and Fearnside 1999, Cochrane and Schulze 1999, Cochrane *et al.* 1999, Nepstad *et al.* 1999a,b).

The incidence of fire has increased radically in the Amazon, for two reasons. First, the number of ignition sources has increased by orders of magnitude since European colonization. Fire is used commonly in the Amazon today, to clear forests, destroy slash piles, and help control weeds in pastures. Over a 4-month period in 1997, satellite images revealed nearly 45,000 separate fires in the Amazon (P. Brown 1998), virtually all of

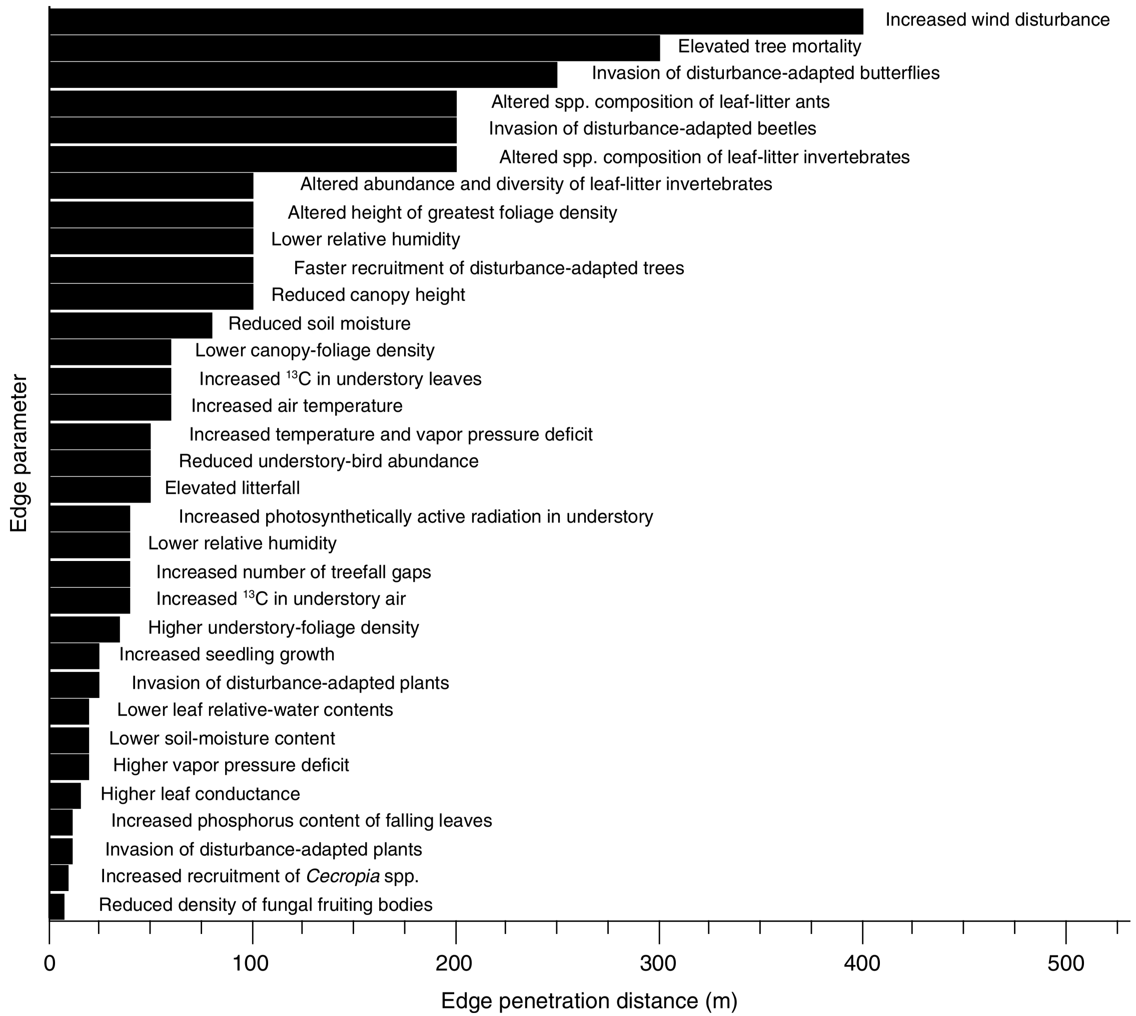

Figure 27.4 When fragmented, Amazonian forests are altered by a great diversity of edge effects that penetrate to varying distances into forest interiors (after Laurance *et al.* 2002b).

Figure 27.5 Ground-fires can penetrate several kilometers into forests, killing many trees and vines and making forests vulnerable to even more devastating wildfires in the future (photograph by M.A. Cochrane).

them human-caused. During the 1997–1998 El Niño drought, wildfires lit by farmers and ranchers swept through an estimated 3.4 million ha of fragmented and natural forest, savanna, regrowth, and farmlands in the northern Amazonian state of Roraima (Barbosa and Fearnside 1999), and there were many large fires in other locations (Cochrane and Schulze 1998). Smoke from forest burning becomes so bad during strong droughts that regional airports must be closed and hospitals report large increases in the incidence of respiratory problems (Laurance 1998).

Second, human land uses increase the vulnerability of tropical forests to fire. Logged forests are far more susceptible to fires, especially during droughts. Logging increases forest desiccation and woody debris (Uhl and Kauffman 1990), and greatly increases access to slash-and-burn farmers and ranchers, which are the main sources of ignition (Uhl and Buschbacher 1985). The combination of logging, migrant farmers, and droughts was responsible for the massive fires that destroyed millions of hectares of Southeast Asian forests in 1982–1983 and 1997–1998 (Leighton 1986, Woods 1989, N. Brown 1998).

Fragmented forests are also exceptionally vulnerable to fire (Figure 27.5), especially in more seasonal areas of the basin. This is because

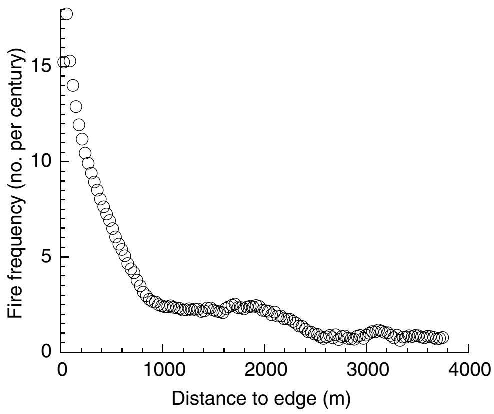

Figure 27.6 Fragmented forests are often extremely vulnerable to fire. Shown is the mean estimated fire frequency as a function of distance from forest edge, for 419 forest fragments in a 2500 km^2 landscape in eastern Amazonia (adapted from Cochrane and Laurance 2002).

fragment edges are prone to desiccation (Kapos 1989) and contain large amounts of flammable litter and wood debris (Nascimento and Laurance 2004), and because forest remnants are juxtaposed with fire-prone pastures, farmlands, and regrowth forests (Gascon *et al.* 2000). Groundfires originating in nearby pastures can penetrate thousands of meters into fragmented forests (Figure 27.6; Cochrane and Laurance 2002). These low-intensity fires kill many trees and increase canopy openings and fuel loads, making the forest far more prone to catastrophic wildfires in the future (Cochrane and Schulze 1999, Cochrane *et al.* 1999). Roughly 45 million ha of forests in Brazilian Amazonia (13% of the total area) are currently vulnerable to edge-related fires (Cochrane 2001).

Additional pressures

Today, even the remotest areas of the Amazon are being influenced by human activities. Illegal gold mining is widespread, with wildcat miners polluting streams with mercury (used to separate gold from sediments) and degrading stream basins with pressure hoses. Illegal miners have also threatened indigenous Amerindians through intimidation and introduction of new diseases (Christie 1997). In addition, increasing numbers of major oil, natural gas, and mineral developments (iron ore, bauxite, gold, copper) are being sanctioned by Amazonian governments (Nepstad *et al.* 1997, Laurance 1998); such projects provide the economic impetus for construction of roads, highways, and transportation networks, which greatly increase forest loss and fragmentation. Finally, hunting pressure is growing throughout the Amazon because of greater access to forests and markets and the common use of shotguns (Alvard *et al.* 1997, Peres 2001). Intensive hunting can alter the structure of animal communities, extirpate species with low reproductive rates, and exacerbate the effects of habitat fragmentation on exploited species (Robinson and Redford 1991).

The magnitude of the human footprint in the Amazon is illustrated by a recent study. Barreto *et al.* (2005) used extensive spatial data on deforestation, urban centers, agrarian reform settlements, hotspots indicating forest fires, areas licensed for mining and mineral reserves, and positions of authorized logging operations to estimate the extent of human activities in the Brazilian Amazon. By 2002, they found, an estimated 47% of the region was under direct human pressure. Their study was conservative because it did not include illegal logging, which is very extensive (e.g., Asner *et al.* 2005), as well as insidious changes such as overhunting that are largely not detectable using available remote-sensing techniques.

FUTURE THREATS

Pressures on Amazonian forests will almost certainly increase in the future. Ultimately, the rapid expansion of the Amazonian population, which rose in Brazil from about 2.5 million in 1960 to over 20 million today (IBGE 2000), is increasing pressures on forests. Such striking growth has mainly resulted from long-term government policies designed to accelerate immigration and economic development in the region, including large-scale colonization schemes, a tax-free development zone, and credit incentives to attract private capital (Moran 1981, Smith 1982, Fearnside 1987, Laurance 2005a). As a result, the Amazon has the highest rate of immigration of any region in Brazil, and has often been characterized as an "escape valve" for reducing overcrowding, social tensions, and displacement of agricultural workers in other parts of the country (Anon. 2001).

Of more immediate importance is that several Amazonian countries have ambitious, near-term plans to develop major infrastructure projects encompassing large expanses of the basin. These projects are intended to accelerate economic development and exports, especially in the industrial agriculture, timber, and mining sectors of the economy. In the Brazilian Amazon, unprecedented investments, on the order of 20 billion dollars, are being fast-tracked to facilitate construction of new highways, roads, railroads, gas lines, hydroelectric reservoirs, power lines, and river-channelization projects (Laurance *et al.* 2001b, Fearnside 2002). Under current schemes, about 7500 km of new paved, all-weather highways will be created. Key environmental agencies, such as the Ministry of the Environment, are being largely excluded from the planning of these developments (Laurance and Fearnside 1999).

The new infrastructure projects have the potential to cause unprecedented forest loss and degradation (Figure 27.7). The once-remote northern Amazon, for example, has been bisected by the BR-174 highway, which spans some 800 km between Manaus and the Venezuelan border, greatly increasing physical access for logging and colonization projects. Other large highways, such as the BR-319 and BR-163, will soon bisect the central-southern Amazon along a north–south axis. Permanent waterways are being constructed that involve channelizing thousands of kilometers of the Madeira, Xingu, Tocantins, and Araquaia rivers, to allow river barges to transport soybeans from rapidly expanding agricultural areas in central Brazil (Fearnside 2001). In addition, planned road projects will traverse large expanses of the southern Amazon and ascend the Andes to reach the Pacific coast, passing through Bolivia, Peru, and northern Chile. A 3000 km natural-gas line is also under construction between Santa Cruz, Bolivia and São Paulo, Brazil (Soltani and Osborne 1994).

If they proceed as currently planned, the new infrastructure projects will be one of the most serious threats to Amazonian forests (Laurance *et al.* 2001a, 2004a). By criss-crossing the basin and greatly increasing physical access to forests, the new projects will open up expansive frontiers for colonization and encourage further immigration into a region that is already experiencing rapid population growth. Forest loss and fragmentation are expected to increase considerably (Figure 27.7). In the future, the resulting forest remnants will be far more vulnerable than are large expanses of intact forest to predatory logging, wildfires, and other degrading activities.

A final concern is that Amazonian forests could be subjected to major environmental alterations as a result of global warming, changes in atmospheric composition, or large-scale land-cover changes that reduce evapotranspiration and alter land–atmosphere interactions (e.g., Laurance 2004, Laurance *et al.* 2004b, Malhi and Phillips 2005 and references therein). Reductions in future precipitation are especially likely to have important impacts on forests. For example, several (but not all) of the leading global circulation models suggest that global warming and increasing deforestation will collectively lead to substantial future declines in Amazonian rainfall (Costa and Foley 2000, Cox *et al.* 2000, Zhang *et al.* 2001). These declines are likely to be most damaging in the large expanses of Amazonian forest that experience strong dry seasons and are already at or near the physiological limit of tropical rainforest. In such areas, the incidence of intentional or unplanned forest fires could rise sharply.

AN EXPANDING NETWORK OF RESERVES

Despite the growing panoply of environmental threats, this is also a period of unparalleled opportunity for conservation in the Amazon. Most notably, Brazil, via various federal and state initiatives, is currently designating many

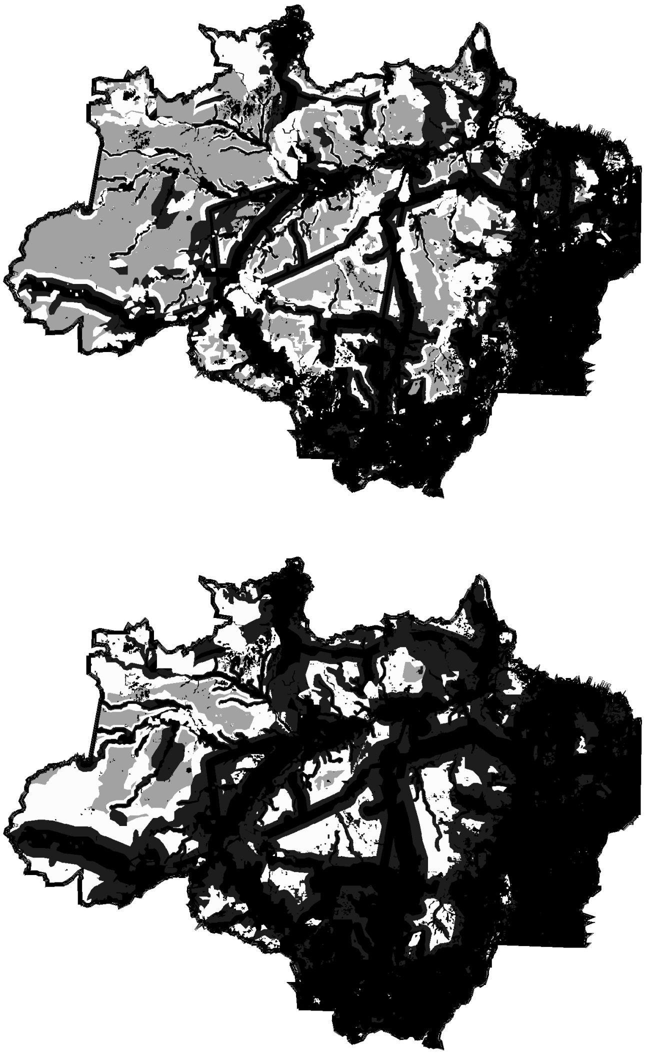

Figure 27.7 Optimistic (above) and non-optimistic (below) scenarios for the Brazilian Amazon, showing predicted forest degradation by the year 2020 (black is deforested or heavily degraded, including savannas and other non-forested areas; dark gray is moderately degraded; white is lightly degraded; and light gray is pristine) (after Laurance *et al.* 2001b).

new Amazonian protected areas and sustainable-use forests (Laurance 2005b, Peres 2005). For example, with an area of nearly 3.9 million ha, the recently designated Tumucumaque Mountains National Park in northeastern Brazil is the largest tropical forest reserve in the world (Mitchell 2002).

The new conservation units in Brazilian Amazonia vary in the kinds of resource uses that are legally permitted (Rylands and Brandon 2005). Intensive uses including industrial logging are permitted in some reserves, such as National Forests and Environmental Protection Areas, whereas other units, such as National Parks, nominally allow only limited uses that include tourism and scientific research. Yet other conservation units, such as Extractive Reserves, permit intermediate activities such as hunting, rubber tapping, and traditional swidden farming (Laurance 2005).

Although less than 5% of the Brazilian Amazon is currently in strict-protection reserves such as

National Parks, this figure will rise in coming years. Via the Amazon Regional Protected Area (ARPA) initiative, the Brazilian federal government has committed to establish a total of 10% of forests in the region (50 million ha) in strict-protected areas (Rylands and Brandon 2005). ARPA is also promoting new "sustainable-use" reserves that allow various types of extractive activities, from rubber tapping to industrial logging, and in which biodiversity conservation is a secondary priority. Although many new reserves have been designated since ARPA's inception in 2002, most are still "paper parks" that as yet have little staffing or infrastructure.

In addition to ARPA, some forward-looking states in the Brazilian Amazon, especially Amapá and Amazonas, are currently establishing many new conservation units, mostly smaller sustainable-use reserves. The Brazilian Amazon also contains several hundred indigenous lands and territories that are controlled by Amerindian tribes. Although not formally considered conservation units, these lands encompass one fifth of the Brazilian Amazon and often have an important role in protecting forests from predatory logging and land development (Schwartzman and Zimmerman 2005). To provide territories for additional Amerindian groups, the network of indigenous lands is likely to increase in the future (Rylands and Brandon 2005).

Strategies for locating reserves in Amazonia have evolved over time. During the 1970s, the initial emphasis was on protecting putative Pleistocene forest refugia, major vegetation formations, suggested phytogeographical regions, and areas with little economic potential (Rylands and Brandon 2005). Today, however, reserve locations are being influenced by three concepts that arose during the mid- to late 1990s. One of these is ARPA, which is focusing on establishing reserves within 23 Amazonian ecoregions, identified by WWF, that encompass major river drainages and vegetation types (Ferreira 2001). Another is a series of expert workshops initiated by Brazil's Ministry for the Environment, which identified 385 priority areas for conservation in Amazonia (MMA 2002). The third is the biodiversity corridor concept, which proposes to link conservation units of various types into several large chains, to help maintain forest connectivity (Ayres *et al.* 1997). Several of the proposed corridors span major rainfall gradients and might, if adequately secured and protected, limit the impacts of future climate change, by enabling species to shift their ranges in response to changing conditions.

CONCLUSIONS

As discussed above, the Amazon has already been substantially altered by human activities, with roughly one fifth of all its forests having been destroyed to date, and larger expanses – perhaps another third of the remaining forest – having been degraded by selective logging, surface fires, habitat fragmentation, and edge effects. Moreover, even many of the remotest areas of the Amazon have been altered to some degree by hunting and by other forms of exploitation such as illegal gold mining. The rapid pace of Amazon forest loss could easily accelerate in the future given current plans for major expansion of transportation infrastructure, with a number of new projects slated to penetrate deep into intact forest tracts. Especially alarming is the prospect that the basin's forests could be fragmented on a large spatial scale, which could dramatically increase the vulnerability of remaining forests to a range of exploitative activities.

Nonetheless, the conservation prognosis is not entirely negative. As has occurred in the past, especially in areas with infertile soils, large expanses of exploited land in the Amazon will be abandoned, usually after cattle ranching, leading to regeneration of secondary forests. These secondary forests are clearly superior to pastures in terms of their hydrological functions and carbon storage. They also provide some habitat for wildlife, but their benefits for old-growth forest species are usually limited where regrowth is young or does not adjoin primary forest (a source of seeds and animal seed dispersers) (Uhl *et al.* 1988, Lamb *et al.* 2005). In the Amazon, many areas of secondary forest are burned after one to several decades to create new pastures (Fearnside 2000).

Perhaps the greatest cause for optimism in the Amazon is the prospect of a major expansion of the current system of protected and semi-protected areas. Although many of these new conservation units will be under multiple-use management and thus can be subjected to intensive uses such as industrial logging, they clearly afford some degree of protection to forests. The growing network of indigenous lands will also help to limit the extent of forest exploitation. The great challenges for the near future are to rapidly expand the existing protected-area network, and to establish direly needed staffing and infrastructure for park management. Such initiatives will be crucial, because pressures on protected areas will increase rapidly in the future as highways and other transportation infrastructure ramify throughout the basin, bringing conservation units and the expanding Amazonian population into ever-closer contact.

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REFERENCES

Abramovitz, J. (1998) *Taking a Stand: Cultivating a New Relationship with the World's Forests.* World Watch Institute, Washington, DC.

Alvard, M.S., Robinson, J.G., Redford, K.H., and Kapland, H. (1997) The sustainability of subsistence hunting in the neotropics. *Conservation Biology* 11, 977–982.

Anon. (1997) Controle sobre florestas exige a reforma do IBAMA. *A Crítica Newspaper*, Manaus, Brazil, January 19.

Anon. (2001) Amazônia cede as terras e o governo se esquece das verbas. *O Liberal*, Belém, Brazil, April 4.

Asner, G.P., Knapp, D., Broadbent, E., Oliveira, P., Keller, M., and Silva, J. (2005) Selective logging in the Brazilian Amazon. *Science* 310, 480–482.

Ayres, J.M., da Fonseca, G.A.B., Rylands, A.B., Quieroz, H.L., Pinto, I.P., and Cavalcanti, R. (1997) *Abordagens inovadoras para conservação da biodiversidade no Brasil: os corridores das florestas neotropicais.* Ministério do Meio Ambiente, Brasília, Brazil.

Barbosa, R.I. and Fearnside, P.M. (1999) Incêndios na Amazônia brasileira: estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). *Acta Amazonica* 29, 513–534.

Barreto, P., Souza, C., Anderson, A., Salomão, R., Wiles, J., and Noguerón, R. (2005) *Human Pressure in the Brazilian Amazon.* Technical report, Institute of People and the Environment in the Amazon (IMAZON), Belém, Brazil.

Bennett, E.L. and Gumal, M.T. (2001) The interrelationships of commercial logging, hunting, and wildlife in Sarawak: recommendations for forest management. In R. Fimbel, A. Grajal, and J.G. Robinson (eds), *The Cutting Edge: Conserving Wildlife in Logged Tropical Forests*. Columbia University Press, New York, pp. 359–374.

Bierregaard, R.O. Jr., Lovejoy, T.E., Kapos, V., dos Santos, A., and Hutchings, R.W. (1992) The biological dynamics of tropical rainforest fragments. *BioScience* 42, 859–866.

Brown, K.S. (1987) Soils and vegetation. In T.C. Whitmore and G.T. Prance (eds), *Biogeography and Quaternary History in Tropical America*. Oxford Monographs in Biogeography 3. Oxford, pp. 19–45.

Brown, K.S. Jr. and Hutchings, R.W. (1997) Disturbance, fragmentation, and the dynamics of diversity in Amazonian forest butterflies. In W.F. Laurance and R.O. Bierregaard, Jr. (eds), *Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities.* University of Chicago Press, Chicago, pp. 91–110.

Brown, N. (1998) Out of control: fires and forestry in Indonesia. *Trends in Ecology and Evolution* 13, 41.

Brown, P. (1998) Forest fires: setting the world ablaze. *The Guardian*, London, England, March 20.

Carvalho, G., Barros, A.C., Moutinho, P., and Nepstad, D.C. (2001) Sensitive development could protect the Amazon instead of destroying it. *Nature* 409, 131.

Carvalho, K.S. and Vasconcelos, H.L. (1999) Forest fragmentation in central Amazonia and its effects on litter-dwelling ants. *Biological Conservation* 91, 151–158.

Christie, M. (1997) Yanomami Indians appeal for help against invaders. *Reuters News Service*, August 31.

Cochrane, M.A. (2001) In the line of fire: understanding the impacts of tropical forest fires. *Environment* 43, 28–38.

Cochrane, M.A., Alencar, A., Schulze, M.D. *et al.* (1999) Positive feedbacks in the fire dynamics of closed canopy tropical forests. *Science* 284, 1832–1835.

Cochrane, M.A. and Laurance, W.F. (2002) Fire as a large-scale edge effect in Amazonian forests. *Journal of Tropical Ecology* 18, 311–325.

Cochrane, M.A. and Schulze, M.D. (1998) Forest fires in the Brazilian Amazon. *Conservation Biology* 12, 948–950.

Cochrane, M.A. and Schulze, M.D. (1999) Fire as a recurrent event in tropical forests of the eastern Amazon: effects on forest structure, biomass, and species composition. *Biotropica* 31, 2–16.

Colchester, M. (1994) The new sultans: Asian loggers move in on Guyana's forests. *Ecologist* 24, 45–52.

Costa, M. and Foley, J. (2000) Combined effects of deforestation and doubled atmospheric CO_2 concentrations on the climate of Amazonia. *Journal of Climate* 13, 18–34.

Cox, P.M., Betts, R.A., Jones, C.D., Spall, S.A. and Totterdell, I.J. (2000) Acceleration of global warming due to carbon cycle feedbacks in a coupled climate model. *Nature* 408, 184–187.

Dale, V.H. and Pearson, S.M. (1997) Quantifying habitat fragmentation due to land-use change in Amazonia. In W.F. Laurance and R.O. Bierregaard, Jr. (eds), *Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities*. University of Chicago Press, Chicago, pp. 400–409.

Didham, R.K., Ghazoul, J., Stork, N.E., and Davis, A.J. (1996) Insects in fragmented forests: a functional approach. *Trends in Ecology and Evolution* 11, 255–260.

Fearnside, P.M. (1987) Causes of deforestation in the Brazilian Amazon. In R.F. Dickinson (ed.), *The Geophysiology of Amazonia: Vegetation and Climate Interactions*. John Wiley, San Francisco, pp. 37–61.

Fearnside, P.M. (1990) Environmental destruction in the Amazon. In D. Goodman and A. Hall (eds), *The Future of Amazonia: Destruction or Sustainable Development?* Macmillan, London, pp. 179–225.

Fearnside, P.M. (1993) Deforestation in the Brazilian Amazon: the effect of population and land tenure. *Ambio* 8, 537–545.

Fearnside, P.M. (1997) Protection of mahogany: a catalytic species in the destruction of rain forests in the American tropics. *Environmental Conservation* 24, 303–306.

Fearnside, P.M. (2000) Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* 46, 115–158.

Fearnside, P.M. (2001) Soybean cultivation as a threat to the environment in Brazil. *Environmental Conservation* 28, 23–38.

Fearnside, P.M. (2002) Avança Brasil: environmental and social consequences of Brazil's planned infrastructure in Amazonia. *Environmental Management* 30, 735–747.

Ferreira, L.V. (2001) Identifição de áreas prioritárias para a conservação da biodiversidade por meio da representatividade das unidades de conservação e tipos de vegetação nas ecorregiões da Amazônia brasiliera. In A. Verissimo, A. Moreira, D. Sawyer, I. dos Santos, L. Pinto, and J. Capobianco (eds), *Biodiversidade na Amazônia brasileira: avaliação e ações prioritárias para conservação, uso sustentável e repartição de benefícios*. Editora Estação Liberdade, São Paulo, Brazil, pp. 211–245.

Gascon, C., Williamson, G.B., and da Fonseca, G.A.B. (2000) Receding forest edges and vanishing reserves. *Science* 288, 1356–1358.

Homma, A.K.O., Walker, R.T., Scatena, F. *et al.* (1992) *A dinâmica dos desmatamentos e das queimadas na Amazônia: uma análise microeconômica.* Unpublished manuscript, EMBRAPA, Belém, Brazil.

IBGE (1997) *Diagnóstico ambiental da Amazônia Legal. CD-ROM with GIS version of RADAM maps*. Institute for Geography and Statistics (IBGE), Brasília, Brazil.

IBGE (2000) *Censo Demográphico, Dados Distritais: XI Recenseamento Geral do Brasil 2000*. Brazilian Institute of Geography and Statistics, Brasília.

INPE (2005) *Deforestation Estimates in the Brazilian Amazon*. National Institute for Space Research (INPE), São Jose dos Campos, Brazil.

Johns, A. (1997) *Timber Production and Biodiversity Conservation in Tropical Rain Forests.* Cambridge University Press, Cambridge.

Kaimowitz, D., Mertens, B., Wunder, S., and Pacheco, P. (2004) *Hamburger connection fuels Amazon destruction.* Technical report, Center for International Forest Research, Bogor, Indonesia.

Kapos, V. (1989) Effects of isolation on the water status of forest patches in the Brazilian Amazon. *Journal of Tropical Ecology* 5, 173–185.

Kauffman, J.B. (1991) Survival by sprouting following fire in tropical forests of the eastern Amazon. *Biotropica* 23, 219–224.

Klein, B.C. (1989) Effects of forest fragmentation on dung and carrion beetle communities in central Amazonia. *Ecology* 70, 1715–1725.

Lamb, D., Erskine, P.D., and Parotta, J.A. (2005) Restoration of degraded tropical forest landscapes. *Science* 310, 1628–1632.

Laurance, S.G.W., Stouffer, P.C., and Laurance, W.F. (2004) Effects of road clearings on movement patterns of understory rainforest birds in central Amazonia. *Conservation Biology* 18, 1099–1109.

Laurance, W.F. (1998) A crisis in the making: responses of Amazonian forests to land use and climate change. *Trends in Ecology and Evolution* 13, 411–415.

Laurance, W.F. (2004) Forest–climate interactions in fragmented tropical landscapes. *Philosophical Transactions of the Royal Society B* 359, 345–352.

Laurance, W.F. (2005a) Razing Amazonia. *New Scientist*, October 15, pp. 34–39.

Laurance, W.F. (2005b) When bigger is better: the need for Amazonian megareserves. *Trends in Ecology and Evolution* 20, 645–648.

Laurance, W.F., Albernaz, A.K.M., and Da Costa, C. (2001a) Is deforestation accelerating in the Brazilian Amazon? *Environmental Conservation* 28, 305–311.

Laurance, W.F., Albernaz, A.K.M., Fearnside, P.M., Vasconcelos, H.L., and Ferreira, L.V. (2004a) Deforestation in Amazonia. *Science* 304, 1109.

Laurance, W.F., Albernaz, A.K.M., Schroth, G., Fearnside, P.M., Ventincinque, E., and Da Costa, C. (2002a) Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography* 29, 737–748.

Laurance, W.F. and Bierregaard, R.O. Jr. (eds) (1997) *Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities.* University of Chicago Press, Chicago.

Laurance, W.F. and Cochrane, M.A. (2001) Synergistic effects in fragmented landscapes. *Conservation Biology* 15, 1488–1489.

Laurance, W.F., Cochrane, M.A., Bergen, S. *et al.* (2001b) The future of the Brazilian Amazon. *Science* 291, 438–439.

Laurance, W.F., Delamonica, P., Laurance, S.G., Vasconcelos, H., and Lovejoy, T.E. (2000) Rainforest fragmentation kills big trees. *Nature* 404, 836.

Laurance, W.F. and Fearnside, P.M. (1999) Amazon burning. *Trends in Ecology and Evolution* 14, 457.

Laurance, W.F., Ferreira, L.V., Rankin-de Merona, J.M., and Laurance, S.G. (1998a) Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology* 79, 2032–2040.

Laurance, W.F., Laurance, S.G., and Delamonica, P. (1998b) Tropical forest fragmentation and greenhouse gas emissions. *Forest Ecology and Management* 110, 173–180.

Laurance, W.F., Laurance, S.G., Ferreira, L.V., Rankin-de Merona, J., Gascon, C., and Lovejoy, T.E. (1997) Biomass collapse in Amazonian forest fragments. *Science* 278, 1117–1118.

Laurance, W.F., Lovejoy, T.E., Vasconcelos, H.L. *et al.* (2002b) Ecosystem decay of Amazonian forest fragments: a 22-year investigation. *Conservation Biology* 16, 605–618.

Laurance, W.F., Oliveira, A.A., Laurance, S.G. *et al.* (2004b) Pervasive alteration of tree communities in undisturbed Amazonian forests. *Nature* 428, 171–175.

Laurance, W.F. and Peres, C.A. (eds) (2006) *Emerging Threats to Tropical Forests*. University of Chicago Press, Chicago.

Leighton, M. (1986) Catastrophic drought and fire in Borneo tropical rain forest associated with the 1982–1983 El Niño Southern Oscillation Event. In G.T. Prance (ed.), *Tropical Rain Forests and the World Atmosphere*. Cambridge University Press, Cambridge, England, pp. 75–102.

Lovejoy, T.E. (1999) Preface. *Biological Conservation* 91, 100.

Lovejoy, T.E., Bierregaard, R.O., Rylands, A. *et al.* (1986) Edge and other effects of isolation on Amazon forest fragments. In M.E. Soule (ed.), *Conservation Biology: The Science of Scarcity and Diversity*. Sinauer, Sunderland, MA, pp. 257–285.

Malhi, Y. and Phillips, O.L. (eds) (2005) *Tropical Forests and Global Atmospheric Change*. Oxford University Press, Oxford.

Meggers, B.J. (1994) Archeological evidence for the impact of mega-Niño events on Amazonian during the past two millennia. *Climatic Change* 28, 321–338.

Mitchell, A. (2002) Brazil unveils project to save rain forest. *The Globe and Mail*, UK, September 7.

MMA (2002) *Biodiversidade brasileira: avaliação e identificação de áreas e acões prioritárias para conservação, utilização sustentável e repartição de benefícios da biodiversidade brasileira*. Ministério do Meio Ambiente, Brasília, Brazil.

Moran, E.F. (1981) *Developing the Amazon*. University of Indiana Press, Bloomington.

Muggiati, A. and Gondim, A. (1996) Madeireiras. *O Estado de S. Paulo*, São Paulo, Brazil, September 16.

Nascimento, H.E.M. and Laurance, W.F. (2004) Biomass dynamics in Amazonian forest fragments. *Ecological Applications* 14, S127–S138.

Nepstad, D.C., Carvalho, C., Davidson, E. *et al.* (1994) The role of deep roots in the hydrological cycles of Amazonian forests and pastures. *Nature* 372, 666–669.

Nepstad, D.C., Klink, C., Uhl, C. *et al.* (1997) Land-use in Amazonia and the cerrado of Brazil. *Ciencia e Cultura* 49, 73–86.

Nepstad, D.C., Moreira, A.G., and Alencar, A.A. (1999a) *Flames in the rain forest: origins, impacts, and alternatives to Amazonian fires.* Pilot Program to Conserve the Brazilian Rain Forest, Brasília, Brazil.

Nepstad, D.C., Verissimo, A., Alencar, A. *et al.* (1999b) Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398, 505–508.

Peres, C.A. (2001) Synergistic effects of subsistence hunting and habitat fragmentation on Amazonian forest vertebrates. *Conservation Biology* 15, 1490–1505.

Peres, C.A. (2005) Why we need megareserves in Amazonia. *Conservation Biology* 19, 728–733.

Piperno, D.R. and Becker, P. (1996) Vegetational history of a site in the central Amazon Basin derived from phytolith and charcoal records from natural soils. *Quaternary Research* 45, 202–209.

Richter, D.D. and Babbar, L.I. (1991) Soil diversity in the tropics. *Advances in Ecological Research* 21, 315–389.

Robinson, J. and Redford, K. (eds) (1991) *Neotropical Wildlife Use and Conservation*. University of Chicago Press, Chicago.

Rylands, A.B. and Brandon, K. (2005) Brazilian protected areas. *Conservation Biology* 19, 612–618.

Saldariagga, J. and West, D.C. (1986) Holocene fires in the northern Amazon basin. *Quaternary Research* 26, 358–366.

Sanford, R.L., Saldariagga, J., Clark, K., Uhl, C., and Herrera, R. (1985) Amazon rain-forest fires. *Science* 227, 53–55.

Sarre, A., Sobral Filho, M., and Reis, M. (1996) The amazing Amazon. *ITTO Tropical Forest Update* 6, 3–7.

Schwartzkopf, L. and Rylands, A.B. (1989) Primate species richness in relation to habitat structure in Amazonian rainforest fragments. *Biological Conservation* 48, 1–12.

Schwartzman, S. and Zimmerman, B. (2005) Conservation alliances with indigenous peoples of the Amazon. *Conservation Biology* 19, 721–727.

Sizer, N. and Rice, R. (1995) *Backs to the Wall in Suriname: Forest Policy in a Country in Crisis*. World Resources Institute, Washington, DC.

Skole, D. and Tucker, C.J. (1993) Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. *Science* 260, 1905–1910.

Smith, N.J.H. (1982) *Rainforest Corridors: The Transamazon Colonization Scheme*. University of California Press, Berkeley, CA.

Soltani, A. and Osborne, T. (1994) *Arteries for Global Trade, Consequences for Amazonia*. Amazon Watch, Malibu, CA.

Steininger, M.K., Tucker, C., Ersts, P., Killeen, T., and Hecht, S. (2001a) Clearance and fragmentation of semi-deciduous tropical forest in the Tierras Bajas zone, Santa Cruz, Bolivia. *Conservation Biology* 15, 856–866.

Steininger, M.K., Tucker, C., Townshend, J. *et al.* (2001b) Tropical deforestation in the Bolivian Amazon. *Environmental Conservation* 28, 127–134.

Stouffer, P.C. and Bierregaard, R.O. (1995) Use of Amazonian forest fragments by understory insectivorous birds. *Ecology* 76, 2429–2445.

Uhl, C., Barreto, P., Verissimo, A. *et al.* (1997) Natural resource management in the Brazilian Amazon. *BioScience* 47, 160–168.

Uhl, C. and Buschbacher, R. (1985) A disturbing synergism between cattle ranch burning practices and selective tree harvesting in the eastern Amazon. *Biotropica* 17, 265–268.

Uhl, C., Buschbacher, R., and Serrão, E. (1988) Abandoned pastures in eastern Amazonia. I. Patterns of plant succession. *Journal of Ecology* 76, 633–681.

Uhl, C. and Kauffman, J.B. (1990) Deforestation, fire susceptibility, and potential tree responses to fire in the eastern Amazon. *Ecology* 71, 437–449.

Uhl, C. and Vieira, I.C.G. (1989) Ecological impacts of selective logging in the Brazilian Amazon: a case study from the Paragominas region of the state of Pará. *Biotropica* 21, 98–106.

Veríssimo, A., Barreto, P., Mattos, M., Tarifa, R., and Uhl, C. (1992) Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. *Forest Ecology and Management* 55, 169–199.

Veríssimo, A., Barreto, P., Tarifa, R., and Uhl, C. (1995) Extraction of a high-value natural resource in Amazonia: the case of mahogany. *Forest Ecology and Management* 72, 39–60.

Veríssimo, A., Cochrane, M.A., and Souza, C. Jr. (2002) National forests in the Amazon. *Science* 297, 1478.

Viña, A. and Cavalier, J. (1999) Deforestation rates (1938–1988) of tropical lowland forests on the Andean foothills of Colombia. *Biotropica* 31, 31–36.

Walker, G. (1996) Kinder cuts. *New Scientist* 151, 40–42.

Whitmore, T.C. (1997) Tropical forest disturbance, disappearance, and species loss. In W.F. Laurance and R.O. Bierregaard, Jr. (eds), *Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities*. University of Chicago Press, Chicago, pp. 3–12.

Woods, P. (1989) Effects of logging, drought, and fire on tropical forests in Sabah, Malaysia. *Biotropica* 21, 290–298.

Zhang, H., Henderson-Sellers, A., and McGuffie, K. (2001) The compounding effects of tropical deforestation and greenhouse warming on climate. *Climate Change* 49, 309–338.