Chapter --

THE FUTURE OF THE AMAZON

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What is happening to the forests of the Amazon today? What will the region be like in another twenty years? Which areas are most vulnerable, and which stand a chance of surviving the coming decades largely intact? In this chapter we grapple with these thorny questions. If you are interested in the Amazon but are not up-to-date on all the development issues, trends, and controversies, then this chapter was written for you.

Obviously, parts of this chapter are speculative--this is the nature of prognostication. In developing our predictions it was necessary to adopt a coarse-grained approach: here we are predicting broad, basin-wide patterns of forest conversion, not specific, local-scale patterns, because such fine-scale predictions would undoubtedly prove rife with errors.

We begin by summarizing the principal threats to the Amazon today--deforestation, logging, forest fragmentation, and wildfires. We then attempt to predict the pattern and scale of forest conversion over the next two decades based on current trends in deforestation, human migration, and planned and existing highways, roads, and infrastructure projects.

THE AMAZON TODAY

The Amazon contains nearly 60% of the world's remaining tropical rainforest (Whitmore 1997). Closed-canopy forests in the basin encompass about 5.3 million square kilometers, an area the size of western Europe (Sarre et al. 1996). By far the largest forest type is *terra-firme*—forests that are not seasonally flooded. There also are extensive 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, there are scattered savannas and open forests in drier areas of the basin, where narrow strips of rainforest vegetation (termed "gallery forest") often persist along permanent rivers and streams (IBGE 1997).

Most of the Amazon is flat or undulating, occurs at low elevation (<300 m), and overlays poor soils. About four-fifths of the Amazon's soils are classified as latosols (Brown 1987, Sarre et al. 1996), which are typically heavily weathered, acidic, high in toxic aluminum, and poor in nutrients such as phosphorus, calcium, and potassium. Clay particles in these soils can form tight aggregations, giving the soils poor water-holding characteristics, even with high clay contents (Richter and Babbar 1991). The most 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 (see Ruokolainen et al., chap. 12) and thus their soils are far less heavily weathered.

There is a strong gradient in rainfall and seasonality in 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.

CURRENT THREATS TO THE AMAZON

Deforestation

In the past, 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. More of the Brazilian Amazon's forest has been destroyed over 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 dramatically in recent decades (Sarre et al. 1996, Viña and Cavalier 1999, Steininger et al. 2001a, 2001b).

Deforestation rates in the Amazon probably average 3-4 million ha per year—larger than the total area of Belgium. The most reliable deforestation statistics are for the Brazilian Amazon, which have been produced annually since 1990 (except 1993) based on Landsat TM images (INPE 1996, 1998, 2000). Despite various initiatives to slow forest loss, deforestation in Brazilian Amazonia increased through the 1990s (Fig. 1). Annual deforestation rates rose significantly (P=0.041, one-tailed t-test with log-transformed data) between the first and second halves (1990-94 vs. 1995-99) of the decade (Laurance et al. 2001a). (Economic conditions influenced these trends; 1991 was an exceptionally low year because Brazilian bank accounts were frozen, while 1995 was an exceptionally high year because available investment funds increased following government economic reforms; Fearnside 1999).

There are two main causes of deforestation in the Amazon today. The first 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 are estimated to cause

70-75% of all deforestation in the Brazilian Amazon (Fearnside 1993, Nepstad et al. 1999a), and account for much forest loss elsewhere in Latin America (e.g. Viña and Cavalier 1999).

The second major cause of deforestation is slash-and-burn farming, typically conducted by small landowners who clear small (1-2 ha) areas of forest each year. 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 brief 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 (50-200 ha) to individual families. Brazil has hundreds of Amazonian colonization projects involving millions of people, initiated in part to help divert population flows that would otherwise further overcrowd Brazil's major cities (Fearnside 1990, 1993).

A third cause of deforestation, industrial agriculture, is increasing very rapidly in importance along the drier southern margins of the Amazon (and also in drier areas in the east-central Amazon near Santarem) and adjoining transitional forests and *cerrado* woodlands and savannas. Most of these farms are devoted to soybeans, which involves clearing large expanses of flat land for crop production (Fearnside 2001, Steininger et al. 2001a, 2001b).

Logging

Industrial logging is increasing dramatically in the Amazon. Tropical logging is usually selective, in that only a small percentage of trees are harvested, although the number of harvested species varies considerably among regions. In new Amazonian frontiers, for example, only 5-15 species are typically harvested (1-3 trees/ha), but 100-150 species are harvested in older frontiers (5-10 trees/ha)(Uhl et al. 1997). Valuable timbers such as mahogany (*Swietenia* spp.) are often overexploited and play a key role in making logging operations profitable (Fearnside 1997).

The direct impacts of logging mostly arise from the networks of roads, tracks, and small clearings created during cutting operations (Fig. 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, Verissimo et al. 1992, 1995, Johns 1997). In addition, logging has important indirect effects; by creating labyrinths of forest roads, logging opens up areas for colonization by migrant settlers who often use destructive slash-and-burn farming methods (Uhl and Buschbacher 1985, Verissimo et al. 1995, Laurance 2001). Logging also allows a sharp increase in hunting, which can dramatically affect some wildlife species. In the Malaysian state of Sarawak, for example, one logging camp was estimated to consume over 30,000 kg of wildlife meat each year (Bennett and Gumal 2001).

In recent years, multinational timber companies from Malaysia, Indonesia, South Korea, and other Asian countries have moved rapidly into the Brazilian Amazon by buying large forest tracts, often obtained by purchasing interests in local timber firms. In Guyana, Suriname, and Bolivia, Asian corporations have obtained long-term forest leases (termed "concessions"; Colchester 1994, Sizer and Rice 1995). In 1996 alone, Asian companies invested more than $500 million in the Brazilian timber industry (Muggiati and Gondim 1996). Asian multinationals now 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 the Brazilian government 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 a controversial effort to gain better control over logging operations, in 1997 Brazil opened 39 of its National Forests (totaling 14 million ha) to logging, arguing that logging concessions would not be granted to companies with poor environmental records (Anon. 1997). Much larger areas of the Brazilian Amazon are likely to be designated as logging reserves in the future (Verissimo et al. 2002).

Forest Fragmentation

The rapid pace of deforestation is leading to widespread forest fragmentation. Habitat fragmentation has myriad effects on Amazonian forests, such as altering the diversity and composition of fragment biotas, 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, Laurance et al. 2002). Edge effects—ecological changes associated with the abrupt, artificial edges of forest fragments—penetrate at least 300 m into Amazonian forests (Laurance et al. 1997, 1998a, 2000) and possibly much further (Skole and Tucker 1993, Laurance 2000).

One key study found that 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 over 150% larger than the area that had actually been deforested (Skole and Tucker 1994). Because over 14% of the region’s forests has now been cleared (INPE 1996, 1998, 2000), the total area affected by fragmentation, deforestation, and edge effects could comprise a third of the Brazilian Amazon today (Laurance 1998). This figure would probably rise if the extensive areas affected by logging and ground-fires were included, but such changes are difficult to detect (Stone and Lefebvre 1998) and have not been quantified in the satellite images used to map Amazon deforestation (Nepstad et al. 1999b).

Forest fragmentation is occurring at many spatial scales. On a regional scale, the once-remote interior of the Amazon is being dissected by major highways, power lines, and transportation projects, which inevitably lead to rapid deforestation. On a local scale, different land-uses tend to generate characteristic patterns of fragmentation. Cattle ranchers, for example, typically destroy large, rectangular blocks of forest, and habitat fragments that persist in such landscapes are somewhat regular in shape (Fig. 3). Forest-colonization projects, however, result in more complex patterns of fragmentation, creating very irregularly-shaped fragments and a high proportion of forest edge (Dale and Pearson 1997, Laurance et al. 1998b). The resulting spatial pattern has been likened to the ribs of a fish (Fig. 3).

Wildfires
Under natural conditions, large-scale fires are very rare in Amazonian rainforests, 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). (However, some drier Amazon forest formations, such as sandy-soil campinaranas, apparently burned more frequently than did primary rainforest; B. W. Nelson, pers. comm.). Closed-canopy tropical forests are poorly adapted to fire (Uhl and Kauffman 1990), and even light ground-fires can cause high tree mortality (Kauffman 1991, Barbosa and Fearnside 1999, Cochrane and Schulze 1999, Cochrane et al. 1999, Nepstad et al. 1999a).

Fire is used commonly in the Amazon today, to clear forests, destroy slash piles, and help control weeds in pastures. Over a four-month period in 1997, satellite images revealed nearly 45,000 separate fires in the Amazon (P. Brown 1998), virtually all of them human-caused. During drought years, smoke from forest burning becomes so bad that regional airports must be closed and hospitals report dramatic increases in the incidence of respiratory problems (Laurance 1998).

Human land-uses dramatically increase the incidence of fire in tropical forests. 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 are responsible for the massive fires that destroyed millions of hectares of Southeast Asian forests in 1982-83 and 1997-98 (Leighton 1986, Woods 1989, N. Brown 1998).

Fragmented forests are also vulnerable to fire. This is because fragment edges are prone to desiccation (Kapos 1989) and because forest remnants are juxtaposed with fire-prone pastures, farmlands, and regrowth forests. Ground fires (Fig. 4) originating in nearby pastures can penetrate hundreds to thousands of meters into fragmented forests (Kauffman 1991, 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 et al. 1999, Cochrane and Schulze 1999). During the 1997/98 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).

Available evidence suggests that there might be a "deforestation threshold", above which landscapes become far more prone to fires. This could potentially occur as a result of positive feedbacks among deforestation, regional drying, smoke, and fire (Cochrane and Schulze 1999, Cochrane et al. 1999, Nepstad et al. 1999a,b, Laurance and Williamson 2001). Amazonian forests recycle at least half of all rainfall back into the atmosphere, helping to maintain frequent rains, lower surface temperatures, and moderate dry seasons (Salati and Vose 1984). Regional deforestation can reduce rainfall (IPCC 1996), making forests more fire prone and, in turn, promoting additional deforestation and fires. Smoke particles from fires further reduce rainfall by trapping microdroplets of water in the atmosphere, precluding the formation of raindrops (Rosenfeld 1999). Such positive feedbacks are most likely in the drier eastern, southern, and north-central areas of the Amazon, where rainforests are already near their physiological limits (Nepstad et al. 1998).

Ancillary Threats

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 Indians through intimidation and introductions of new diseases (Christie 1997). In addition, there are increasing numbers of major oil, natural gas, and mineral developments sanctioned by Amazonian governments (Nepstad et al. 1997, Laurance 1998). Finally, hunting pressure is growing throughout the Amazon because of greater access to forests and markets and the common use of shotguns (Peres 2001). Intensive hunting can dramatically 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).

FUTURE THREATS TO THE AMAZON

Below we highlight several proximate and ultimate factors that will affect future development trends in the Amazon. These relate mainly to projected changes in population size, infrastructure development, and the spatial patterns of forest conversion (cf. Laurance et al. 2001b, 2001c).

Population Growth

The human population of the Amazon is increasing rapidly, for two reasons. First, populations are growing throughout Latin America, nearly tripling (from 166 to 448 million) between 1950 and 1990 (Mahar and Schneider 1994). Although the traditionally high fertility rates of Latin American women have declined in recent decades, the momentum of population growth will continue for some time because a large proportion of the population is young or still in their child-bearing years. In addition, Amazonian residents often begin bearing children early--in their late teens or early twenties--which contributes substantially to rapid population growth.

Second, there is much immigration into the Amazon. In Brazil, poor economic conditions and droughts in the northeast, limited opportunities in large cities, the displacement of agricultural workers by mechanized farming, and government colonization programs designed to reduce urban overcrowding and help secure the Amazonian frontier have all contributed to a major influx of immigrants into the Amazon (Fearnside 1987, 1990, 1993). As a result of immigration and rapid growth, the population of the Brazilian Amazon has increased twice as fast as the rest of Brazil, rising from 2 million in the 1960s to over 20 million today (Laurance et al. 2001a).

Changing Patterns of Deforestation

The spatial patterns of Amazonian forest conversion are changing in alarming ways. Historically, large-scale deforestation has been most intensive in the eastern and southern areas of the Amazon (the "arc of deforestation"), in the Brazilian states of Pará, Maranhão, Rondônia, Acre, and Mato Grosso, and in northern Bolivia (Skole and Tucker 1993). Since the 1960s, forest conversion has risen dramatically in these areas as a result of large-scale ranching, logging, international development projects, government-sponsored colonization schemes, mining, hydroelectric dams, and land speculation (Fearnside 1987, 1990, 1995, Dale and Pearson 1997, Nepstad et al. 1997, Steininger et al. 2001a, 2001b). There also has been considerable forest clearing along rivers and in parts of the northern and western Amazon--in Ecuador, Colombia, Peru, and Roraima (Brazil).

But this picture is rapidly changing. Major new highways, roads, and transportation projects are now dissecting the heart of the basin, providing access to areas once considered too remote for development. One of the most ambitious new highways, BR-174, runs from the city of Manaus in central Amazonia, northward to the Venezuelan border, spanning a distance of over 1,000 km. Almost fully graded and paved, it was initially promoted as a surgical cut through the forest to provide direct access to Caribbean ports and markets in Venezuela. In 1997, however, Brazilian President Fernando Henrique Cardoso announced that 6 million ha of land along the highway would be opened to settlement, and boasted that the area to be farmed would be "so colossal that it would double the nation's agricultural production" (de Cassia 1997). This highway is already promoting rapid forest clearing, especially within 100 km of Manaus.

As a result of logging booms and rapidly increasing development, central and northern Amazonian cities such as Manaus, Santarém, and Boa Vista are burgeoning. Ongoing construction to link Manaus to Rondônia in southern Amazonia by paving highway BR-319 will provide greatly increased access to the region for migrant settlers, and raises the alarming prospect that over the next decade Amazonian forests could be bisected by an expanding swath of deforestation and logging (Laurance 1998).

New Infrastructure Projects

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 agriculture, timber, and mining sectors of the economy. In the Brazilian Amazon, massive investments, on the order of $40 billion in the years 2000-2007, are being implemented to fast-track construction of dozens of major infrastructure projects—highways, railroads, gas lines, hydroelectric projects, power lines, and river-channelization projects (Anon. 1999, Avança Brasil 1999). The Amazonian road network is being rapidly expanded and upgraded, with many unpaved sections being converted to paved, all-weather highways. Key environmental agencies, such as the Ministry of the Environment, are being largely excluded from the planning of these developments (Laurance and Fearnside 1999, Laurance et al. 2001b).

One indicator of the scale of planned development is the rapidly expanding network of hydroelectric dams. At least 19 major (100-13,000 megawatt) dams are planned in the Brazilian Amazon over the next 10-20 years, nearly all in forested areas (Eletrobrás 1998). These new dams will vastly increase the 600,000 ha of forest that is currently inundated by reservoirs (because the region is quite flat, Amazonian hydroelectric reservoirs are often very large; Fearnside 1995). Most of these dam sites are in tributaries flowing northward into the Amazon River from Brazil's central plateau (the Tocantins, Araguaia, Xingu, and Tapajós Rivers), a region with a high concentration of indigenous peoples (Fearnside 1990). In addition to destroying forests and degrading aquatic systems, hydroelectric dams require networks of access roads and power-line clearings, which promote further forest loss and fragmentation.

New infrastructure projects will dissect vast expanses of the Amazon. The once-remote northern Amazon, for example, has been bisected by the BR-174 highway from Manaus to Venezuela, and will soon be cut by a road link between the rapidly growing city of Boa Vista and Guyana and by a major power-line corridor linking Guri Dam in Venezuela with Boa Vista. These projects will affect large expanses of forest and many indigenous groups in the northern Amazon (Soltani and Osborne 1994), and will greatly increase access to the region for loggers, ranchers, miners, and colonists.

Other projects are equally ambitious. When completed, the massive Ferronorte Railway will be the largest transportation project in Brazil, traversing over 4,000 km of Amazonian forest while linking the cities of Santarém (along the Amazon River) and Porto Velho (in Rondônia) to those in southern Brazil. In the central and eastern Amazon, permanent waterways are being constructed that involve channelizing the Madeira, Tocantins, and Araquaia Rivers, in order to allow deep-water river barges to transport soybeans from rapidly expanding agricultural areas in central Brazil (Fearnside 2001). In the southern Amazon, planned road projects will traverse large expanses of forest and ascend the Andes to reach the Pacific coast, passing through Bolivia, Peru, and northern Chile. In addition, a 3000-km natural gas line currently under construction will run from Santa Cruz, Bolivia to São Paulo, Brazil (Soltani and Osborne 1994).

Logging and Mining Booms

Increasingly, logging and mining activities are becoming important driving forces in the exploitation of the Amazonian frontier. Timber, petroleum, natural gas, and mineral resources (iron ore, bauxite, gold, copper; Sarre et al. 1996) provide the economic impetus for construction of roads, highways, and transportation networks, which greatly increase access to forests for colonists, ranchers, and land speculators. Roads created for oil exploration and development in Amazonian Ecuador have caused a drastic increase in forest colonization, land speculation, and commercial hunting (Holmes 1996). Similar trends are likely in the Peruvian Amazon, much of which is currently being opened for oil and gas concessions (Fig. 5). Logging operations also greatly increase access to frontier areas; it has been estimated that 10,000 to 15,000 km^2 of forest is being logged each year in the Brazilian Amazon alone, a figure nearly as large as the area being deforested each year (Nepstad et al. 1999a,b).

PREDICTING THE FUTURE OF THE BRAZILIAN AMAZON

Here we attempt to predict the scale and pattern of Amazonian forest degradation over the next two decades. We confine our predictions to the Brazilian Legal Amazon, which comprises about two-thirds of the basin (ca. 4.9 million km^2), because accurate spatial data on deforestation, transportation networks, and planned infrastructure projects for the other Amazonian and Guianan countries were very difficult to acquire on a consistent basis. Our analysis is based on a GIS (geographic information system) model that integrates spatial data on existing and planned development activities.

GIS Data Layers

To develop our model, we used the best and most recent available information on forest cover, rivers, planned and existing roads and infrastructure projects, fire proneness of forests, logging and mining intensity, and various conservation units (Table 1). Principal data sources for forest cover, current roads and highways, and conservation units were 1:3,000,000- and 1:4,000,000-scale maps produced by Brazilian agencies and conservation organizations, augmented with remote-sensing (Landsat TM and JERS-1 radar) images and personal knowledge. The maps and remote-sensing images were produced from 1995 to late 1999 (Table 1).

Data on new highways and road upgrades and planned infrastructure projects (Fig. 6) were gleaned from recent sources, principally reports and internet data prepared for international investors by Avança Brasil (1999), as well as the 1998-2007 development plan for Eletrobrás (1998), Brazil's federal electricity utility. The probability of forest fires was based on the map of Nepstad et al. (1998, 1999a), who integrated extensive data on forest cover, seasonal soil-water availability, recent fires, and logging activity, in order to predict areas of high, moderate, and low fire vulnerability during the 1998 dry season. Maps of the estimated extent of logging (both legal and illegal), industrial mining, and illegal gold-mining were produced by IBAMA (Brazil's national environmental agency) in 1998 (Table 1).

The Brazilian Amazon has a variety of federal and state conservation units that vary considerably in their degree of environmental protection. We identified 13 major types of reserves and parks, which we placed into three general categories (Table 2). "High-protection reserves" include National Parks, Ecological Stations, and Ecological Reserves, which nominally receive strong protection. Sanctioned activities in such areas include research, education, and, often, recreation and tourism.

"Moderate-protection reserves" include National Forests, Extractive Reserves, and Sustainable Development Reserves, among others, which may be legally subjected to nominally "sustainable" levels of industrial logging, agriculture, livestock grazing, hunting, fishing, tourism, and extraction of non-timber products (e.g. rubber, fuelwood, fruits, seeds, fibers). Mining is usually prohibited, although illegal gold mining certainly occurs in some reserves (Table 2).

The final category, "reserves with uncertain protection," includes extensive Indigenous Lands and Reserves that collectively comprise about 18% of the Brazilian Legal Amazon (Table 2). In some areas, these lands may be more effectively protected than National Parks, especially where Amerindians are territorial and repel illegal colonists, loggers, and gold miners. In other areas, however--particularly where Amerindians have frequent contact with outsiders--a corruption of traditional lifestyles can occur. In a number of cases, indigenous groups in Brazil have sold their timber to commercial loggers, permitted wildcat mining, overhunted wildlife, illegally cleared protected lands, invaded national parks, impeded firefighters, and even assaulted government inspectors attempting to control illegal logging (Redford and Stearman 1993, Alvard et al. 1997, Margolis 2000). Hence, environmental protection in Amerindian lands is likely to be highly variable, and will tend to decline as contact with outsiders increases.

Buffer Zones

Roads and infrastructure projects promote forest degradation by greatly increasing human access, and in some cases (such as hydroelectric reservoirs) by destroying large areas of forest directly. To predict the future impacts of planned roads and projects, we assessed the past effects of existing highways and roads on primary-forest cover in the Amazon.

To do this we overlayed the existing road network on the Landsat TM-based Pathfinder map of the Brazilian Amazon for 1992. Many of the region's major highways (e.g. Belém-Brasília, Transamazon, BR-364) were constructed in the 1960s and 1970s, and thus had been in existence for 15-25 years by 1992--roughly comparable to the 20-year time-frame for our predictions. Initially, five "buffer zones" were created around all paved highways (0-10, 11-25, 26-50, 51-75, and 76-100 km on each side of the highway), and the percentage loss of primary-forest cover within each zone was determined. This analysis was then repeated using the entire network of highways and unpaved roads. Clouds, cloud shadows, and rivers were removed from the analysis (<5% of total area). Buffers were truncated if they passed outside the Brazilian Legal Amazon. Deforestation was registered only for closed-canopy forests; losses of other habitats (e.g. savanna) were not included. Analyses were run on a Silicon Graphics Origin supercomputer at the Basic Science and Remote Sensing Initiative, Michigan State University.

As expected, the analyses (Fig. 7) revealed that deforestation strongly increased near highways and roads. Both averaged about 30% forest loss within the 0-10 km buffer zone, but highways had more far-reaching effects than roads, averaging about 20% and 15% forest loss in the 11-25 and 26-50 km zones, respectively. Roads tended to generate more-localized deforestation, with average forest loss declining below 15% further than 25 km from the road.

Networks of roads tend to proliferate near highways, as is evident, for example, along the Belém-Brasília and eastern Transamazon Highways. The most far-reaching effects we observed were the construction of 200-300 km-long state and local roads ramifying out laterally from highways in Pará, Mato Grosso, and Amazonas states (Fig. 6). Road networks are also generated by infrastructure projects, as it is nearly impossible to construct hydroelectric dams, power lines, gas lines, and other major facilities without road access.

Model Assumptions

We used the buffer-zone analyses to help generate two alternative predictions--termed the "optimistic" and "non-optimistic" scenarios--for the future of the Brazilian Amazon. Our models predict the spatial distribution of four broad land-use categories. The first category is “high-impact areas,” which are regions in which primary-forest cover is likely to be absent or markedly reduced, and heavily fragmented. Such areas are highly vulnerable to edge effects, fires, logging, and overhunting, and are severely degraded ecologically. “Moderate-impact areas” have mostly intact primary-forest cover (>85%) but contain localized forest clearings and some roads, and may be affected by logging, mining, hunting, and oil and gas exploration. “Low-impact areas” have nearly intact primary-forest cover (>95%) but can experience illegal gold-mining, small-scale farming, hunting, hand-logging, and non-timber resource extraction (e.g. rubber-tapping). “Pristine areas” have fully intact primary-forest cover and are free from anthropogenic impacts aside from limited hunting, fishing, and swidden farming by traditional indigenous communities.

The optimistic and non-optimistic scenarios differ in that the former assumes that highways, roads, and infrastructure projects will generate more-localized effects, and that conservation areas will be less prone to disturbances (Table 3). The sizes of buffer zones used in the models were necessarily somewhat arbitrary, but have an empirical basis in our analyses of past deforestation. In the non-optimistic scenario, for example, we assumed that paved highways would create a 50 km-wide zone of heavily degraded forests on each side (Table 3), because our analysis suggested that these areas averaged <85% forest cover (Fig. 7). Such areas would be prone to logging, fragmentation, fires, edge effects, and other ecological changes that could affect much of the remaining forest cover (cf. Skole and Tucker 1993, Nepstad et al. 1999b, Cochrane et al. 1999, Gascon et al. 2000, Laurance 2000). Likewise, we conservatively assumed that the lightly degraded zone would extend 100-200 km from paved highways (Table 3), because we observed a number of roads stretching at least 200 km from existing highways.

In both scenarios, logging and wildcat mining were assumed to cause moderate and light forest degradation, respectively (Table 3). However, the models differed in terms of the viability of protected areas. The optimistic scenario assumed that all reserves would remain pristine or only lightly degraded, whereas the non-optimistic model assumed that indigenous lands and moderate-protection reserves (or parts thereof) would be moderately degraded within 50 km of roads or 100 km of highways; otherwise they would be pristine or lightly degraded. The non-optimistic scenario also assumed that high-protection reserves would be lightly degraded near roads and highways (Table 3).

GIS Analyses

All maps and spatial data were georeferenced to a geographic coordinate system, using Imagine 8.3 software (ERDAS 1998). Subsequently, georeferenced digital images were used for vector data-layer construction, using Arc/Info 7.2.1 (ESRI 1999) via heads-up digitizing methods. Road and infrastructure buffers were created with Arc/Info software for the appropriate distances. Data layers were integrated with overlay methodology. Most analyses were performed on a Silicon Graphics Indigo2 workstation at Biological Dynamics of Forest Fragments Project (BDFFP) headquarters in Manaus, Brazil.

Results of the Analyses

The optimistic scenario (Fig. 8) suggests that by the year 2020 there will be continued deforestation in the southern and eastern portions of the Brazilian Amazon, and considerable large-scale fragmentation of forests in the central and southern parts of the basin. The Brazilian Amazon will be nearly bisected by heavily to moderately degraded areas along a north-south axis running from Rondônia to Manaus and northward to Venezuela. Pristine and lightly degraded forests will be fragmented into several blocks, with the largest tract surviving in the western Brazilian Amazon. According to this scenario, pristine forests will comprise just 28.0% of the region, with lightly degraded forests comprising another 28.0%. Almost 27% of the region will be deforested or heavily degraded (Fig. 9).

The non-optimistic scenario (Fig. 8) projects an even more dramatic loss of forests along the southern and eastern areas of the basin. Large-scale fragmentation is also more extensive, with much forest in the central, northern, and southeastern areas persisting only in isolated tracts. The basin is almost completely bisected by a swath of heavily degraded lands along the north-south axis running from Rondônia to Venezuela. There are very few areas of pristine forest aside from those in the western quarter of the region. This scenario predicts that pristine forests will comprise just 4.9% of the region, with lightly degraded forests comprising another 25.4%. Over 40% of the region will be heavily degraded (Fig. 9).

Discussion and Implications

Both of our models suggest that the Brazilian Amazon will be drastically altered by current development plans and prevailing land-use trends over the next twenty years. The principal difference between the models is in the extent of forest loss and fragmentation (Fig. 8) and relative proportions of heavily degraded versus pristine forests (Fig. 9).

Some degree of oversimplification in our models was inevitable. For example, we did not incorporate the effect of population density into our models, in part because we observed that local road density in the Amazon seemed to be a reasonably good surrogate for local population density. It is also apparent that the buffer zones around roads, highways, and infrastructure projects will be more variable spatially than is indicated in our models. While we have incorporated many of the factors that are likely to influence local deforestation (e.g. distance to roads, road quality [paved vs. unpaved], presence and type of protected areas, vulnerability to forest fires, logging and mining activity), it is impossible to include every potentially relevant factor (cf. Laurance et al. 2002 for further analyses of factors that influence Amazonian deforestation).

The optimistic and non-optimistic scenarios vary considerably (Fig. 8), and it is therefore important to ask which is the most realistic. At least two considerations suggest that the non-optimistic scenario may better approximate reality. First, the non-optimistic model realistically assumes that forests with high fire vulnerability will become heavily degraded, while those of moderate vulnerability will become moderately degraded. The model of fire vulnerability we used (Nepstad et al. 1998) was produced for a normal dry season and is therefore conservative, in the sense that much larger areas of the Amazon will become prone to fires during periodic El Niño droughts

(Nepstad et al. 1998, Cochrane and Schulze 1998, 1999).

Second, the non-optimistic model assumes that protected areas within 50 km of highways and roads will be lightly to moderately degraded. In fact, many protected areas in the Amazon are little more than “paper parks” with inadequate protection. Ferreira et al. (1999) evaluated 86 federal parks and protected areas in Brazil and found that 43% were at high to extreme risk because of illegal deforestation, colonization, hunting, isolation of the reserve from other forest areas, and additional forms of encroachment. More than half of all reserves (54.6%) were judged to have nearly non-existent management. For some reserves, even our non-optimistic model may be overly optimistic.

The fates of Amerindian lands will have an important impact on forest conservation, because they currently encompass some 18% of the Brazilian Legal Amazon (and about 21% of the forested area of the region). In many areas, the quality of environmental protection as well as traditional lifestyles have declined markedly as indigenous groups come into more frequent contact with outsiders (Margolis 2000). In this sense, reducing construction of new roads and highways near indigenous lands may be one of the most effective measures to ensure that traditional management systems are not corrupted.

Other investigators have also attempted to predict spatial patterns of Amazonian deforestation. Recent studies by a Brazilian non-governmental organization have attempted to predict the extent of deforestation that will be caused by new highway construction under the Avança Brasil program (Nepstad et al. 2000, 2001, Carvalho et al. 2001), but did not consider the effects of other infrastructure projects (hydroelectric reservoirs, power lines, gas lines, railroads, river-channelization projects, and their associated road networks) on forests (cf. Fearnside 2002). In addition, an ongoing study by C. Souza Jr. (pers. comm.) is using data on existing road networks, logging, and recent fires in order to assess conversion pressure on Brazilian Amazonian forests. Earlier studies, such as those of Kangas (1990) and Bryant et al. (1997), did not incorporate effects of massive planned highway and infrastructure developments under Avança Brasil, and hence are seriously out of date.

Obviously, our models illustrate but two of a potentially infinite number of possible futures for the Brazilian Amazon. While we believe our approach is based on realistic assumptions, it has two limitations. First, our model predictions (Fig. 8) are somewhat difficult to test and verify, especially for lightly degraded forests. Low-intensity selective logging and illegal gold mining, for example, are nearly impossible to detect with remote sensing, although technological improvements could change this in the future. Second, our models rely on specific assumptions about the future drivers of forest degradation (Table 3). Perhaps the most crucial assumption is that current infrastructure projects will proceed as planned and that there will be no major new development initiatives. The unforeseen construction of a new highway, for example, could alter the scale and spatial pattern of forest degradation, reducing the accuracy of our predictions.

In the Amazon, hundreds of millions of dollars are currently being expended on efforts to promote conservation planning, via international programs such as the Pilot Program to Protect the Brazilian Rainforest, bilateral initiatives, and the activities of non-governmental organizations (Laurance and Fearnside 1999; Laurance et al. 2001b). The most important conclusion of our study is that current domestic and international efforts to promote conservation planning in the Brazilian Amazon are likely to be swamped by near-term plans to invest over US$40 billion in Amazonian transportation and infrastructure projects. The environmental impacts are further magnified by population increases, forest colonization projects, and rapidly expanding logging and mining industries. If our models provide even a rough approximation of the future, the forests of the Amazon will be profoundly altered over the next two decades. We conclude that a fundamental reevaluation of criteria used in selecting, planning, and licensing large-scale development projects is urgently needed (cf. Fearnside 2002). Without major policy changes, current development schemes are likely to have dire effects on Amazonian forests.

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Table 1. Data layers used in analyses of land-use trends in Brazilian Amazonia. Infrastructure projects include railroads, hydroelectric reservoirs, power lines, gas lines, and river-channelization projects.

Layer	Data Sources
Current forest cover and rivers	Forest/non-forest coverage produced by the National Oceanographic and Atmospheric Administration based on 1999 AVHRR imagery
Existing highways (paved) and roads (unpaved)	1995 map of Brazilian Legal Amazon (1:3,000,000 scale) produced by Brazilian Institute for Geography and Statistics (IBGE); supplemented by 1999 map of Amazonian protected areas (1:4,000,000 scale, Instituto Socioambiental, São Paulo, Brazil), JERS-1 radar imagery for 1999, and personal knowledge
Planned roads and highways, and highway upgrades	Maps and information provided by the Avança Brasil program (Avança Brasil 1999)
Existing infrastructure projects	1995 IBGE map of Brazilian Legal Amazon, supplemented by personal knowledge
Planned infrastructure projects	Maps and information provided by Avança Brasil (1999), Eletrobrás (1998), and personal knowledge
Fire proneness of forests	Map of areas with high, medium, and low fire vulnerability produced by Nepstad et al. (1998, 1999b), based on analyses of forest cover, seasonal soil moisture, logging activity, and recent fires during the 1998 dry season
Logging and mining activity	1998 map of estimated legal and illegal logging, wildcat gold mining, and industrial mining, produced by IBAMA, Brazil's national environmental agency
Federal and state parks and reserves, national forests, extractive reserves, and indigenous lands and reserves	1995 IBGE map of Brazilian Legal Amazon, supplemented by 1999 map of Amazonian protected areas and personal knowledge

Table 2. Legally permitted activities within conservation areas in the Brazilian Amazon[1].

Type of Area	Recreation & Tourism	Agriculture & Livestock	Logging	Non-timber Harvests	Hunting	Mining
Areas with nominally high protection						
National/State Parks	Yes	No	No	No	No	No

Ecological Reserves	Yes	No	No	No	No	No
Biological Reserves	No	No	No	No	No	No
Ecological Stations	No	No	No	No	No	No
Areas with moderate protection						
National/State Forests	Yes	Yes	Yes	Yes	Yes[2]	No
National Forest Res.	Yes	Yes	Yes	Yes	Yes[2]	No
Extractive Reserves	Yes	Yes	Yes	Yes	Yes[2]	No
State Extractive Forests	Yes	Yes	Yes	Yes	Yes[2]	No
Sustainable Use Forests	Yes	Yes	Yes	Yes	Yes[2]	No
Sustain. Devel. Reserves	Yes	Yes	Yes	Yes	Yes[2]	No
Environ. Protection Areas	Yes	Yes[3]	Yes[3]	Yes[3]	No	Yes[3]
Areas of Relevant Ecological Interest	Yes	Yes[3]	No	Yes[3]	No	No
Areas with uncertain protection						
Indigenous Lands and Reserves	No	Yes	Yes	Yes	Yes	No

[1]Data sources: Rylands (1991), Silva (1996), Olmos et al. (1998), Rylands and Pinto (1998), and Borges et al. (2001); internet websites of IBAMA, Instituto Socioambiental, and IBGE; and communication with Luciene Pohl of Brazil's National Indian Foundation (FUNAI).

[2]Hunting is allowed in some areas; for others information was unavailable.

[3]These activities are not expressly permitted, but because people are allowed to live in these reserves they will certainly occur, at least on a limited scale.

Table 3. Explicit assumptions of "optimistic" and "non-optimistic" GIS models to predict the future of the Brazilian Amazon.

	Optimistic Scenario	***Non-optimistic Scenario***
1) Degradation zones around paved highways (current and planned)		
Heavily degraded zone	0-25 km	0-50 km

Moderately degraded zone	25-50 km	50-100 km
Lightly degraded zone	50-75 km	100-200 km
Pristine zone	>75 km	>200 km
2) Degradation zones around unpaved roads, railroads, power lines, gas lines, industrial mines, and river-channelization projects (current and planned)		
Heavily degraded zone	0-10 km	0-25 km
Moderately degraded zone	10-25 km	25-50 km
Lightly degraded zone	25-50 km	50-100 km
Pristine zone	>50 km	>100 km
3) Degradation zones around hydroelectric reservoirs		
Heavily degraded zone	Area inundated	Area inundated
Moderately degraded zone	0-5 km	0-10 km
Lightly degraded zone	5-10 km	10-25 km
Pristine zone	>10 km	>25 km
4) Degradation zones around major navigable rivers (>900 m wide)		
Heavily degraded zone	0-2 km	0-5 km
Moderately degraded zone	2-5 km	5-10 km
Lightly degraded zone	5-10 km	10-25 km
Pristine zone	>10 km	>25 km
5) Areas prone to logging	Moderately degraded	Mod. degraded
6) Areas prone to wildcat mining	Lightly degraded	Lightly degraded
7) Areas prone to fires		
High vulnerability	Moderately degraded	Heavily degraded
Moderate vulnerability	Lightly degraded	Mod. degraded
8) Conservation areas		
High-protection areas outside buffers	Pristine	Pristine
High-protection areas inside buffers	Pristine	Lightly degraded
Mod.-protection areas outside buffers	Lightly degraded	Lightly degraded
Mod.-protection areas inside buffers	Lightly degraded	Mod. degraded
Indigenous areas outside buffers	Pristine	Lightly degraded
Indigenous areas inside buffers	Lightly degraded	Mod. Degraded

FIGURE CAPTIONS

Fig. 1. Annual deforestation rates in the Brazilian Amazon during the decade of the 1990s. The regression line shows the overall trend. These estimates do not include small clearings (<6.25 ha) or extensive areas affected by logging or ground fires.

Fig. 2. Industrial logging creates labyrinths of roads that promote forest colonization and overhunting (photograph by W. F. Laurance).

Fig. 3. Different land uses produce differing patterns of forest loss and fragmentation. A. Large-scale cattle ranching (near Paragominas, Pará). B. “Fishbone” deforestation pattern associated with forest-colonization projects (near Tailândia, Pará). Each rectangle shows an area of 570 km^2.

Fig. 4. Low-intensity ground fires can penetrate considerable distances into forests, killing many trees making forests vulnerable to devastating wildfires in the future (photograph by M. A. Cochrane).

Fig. 5. Much of the Peruvian Amazon is being opened up for oil and gas exploration and development. Shaded areas show current oil and gas concessions, mostly owned by multinational corporations.

Fig. 6. Existing and planned highways and infrastructure projects in the Brazilian Amazon. Above: highways and roads. Below: major infrastructure projects (“utilities” are gas lines and power lines, while “channels” are river-channelization projects).

Fig. 7. Percentage of closed-canopy forest destroyed by 1992 as a function of distance from paved highways, and from all roads and highways, in the Brazilian Amazon.

Fig. 8. Above: optimistic scenario. Below: non-optimistic scenario. Both scenarios show projected forest degradation in the Brazilian Amazon by the year 2020 (gray=deforested or heavily degraded, including savannas and other non-forested areas; crosshatched=moderately degraded; single hatched=lightly degraded; white=pristine).

Fig. 9. Percentages of Brazilian Amazon forest in various degradation classes according to the optimistic and non-optimistic scenarios.