ROADS TO RUIN: EXPANDING TRANSPORTATION NETWORKS IMPERIL GLOBAL BIODIVERSITY

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"The best thing you could do for the Amazon is to bomb all the roads."

Dr. ENEAS SALATI,
Technical Director, Brazilian Institute for Sustainable Development, Rio de Janeiro, Brazil

"Highways are the seeds of tropical forest destruction."

Dr. THOMAS E. LOVEJOY,
Biodiversity Chair, Thomas H. Heinz Center
Washington, D.C., USA

"In the Congo, rapidly proliferating roads—and the ivory hunters they bring—are decimating the African forest elephant."

Dr. STEPHEN BLAKE,
former Inventory Coordinator of the MIKE (Monitoring of Illegal Killing of Elephants) Program in central Africa

VILIFYING ROADS

As the quotes above illustrate, environmental scientists often take a very dim view of roads and highways in the vicinity of natural ecosystems. This perspective is strikingly different from that of many economists and regional planners, who typically extol the "opening up" of frontier regions by new roads as a good thing (e.g., Simuyemba 2001; Duval 2008). Why such a dramatic difference in perception?

Here I evaluate the impacts of roads from a broad environmental standpoint. At the outset, I describe how and why economic globalization is promoting rapid road expansion in many previously road-free areas. I then highlight the manifold environmental impacts of roads on native ecosystems and wildlife. Finally, I consider some strategies to reduce the impacts and extent of roads. As will quickly become apparent, I hold a deeply ambivalent view of roads: they are a necessary part of contemporary life, but they are sometimes environmentally devastating.

Two caveats are needed before I proceed further. First, in a functional sense there can be a strong distinction between a "highway," which is a major paved thoroughfare that provides year-round access to a region, and a "road," which is generally smaller and may or may not be paved. For simplicity, however, I will use the term "road" for either. Both are examples of linear infrastructure, which also includes power lines, gas lines, railroads, and canals. Linear infrastructures are among the most ubiquitous features of human activity in the world today.

Secondly, I will focus here exclusively on tropical nations. These are the areas I know best, having spent the better part of three decades living and working in them. More importantly, tropical nations harbor much of the world's biodiversity—sustaining at least half of the planet's species in just 7% of its land area (Primack 2006)—and are where roads are expanding most swiftly.

ROADS AND RAINFOREST BIODIVERSITY

Roads and other linear infrastructure have serious environmental impacts on natural habitats worldwide (Forman and Alexander 1998; Trombulak and Frissel 2000), but tropical rainforests seem specially vulnerable (Laurance *et al.*, in press).

Firstly, from a biological perspective, rainforests have a complex architecture and uniquely humid, dark, stable microclimate. They sustain many animal species specialized for living in forest-interior and understory conditions [Figure 1], some of which strongly avoid abrupt forest edges along clearings and rarely cross even narrow forest openings. Other tropical species are vulnerable to hunting, road-kill from vehicles, elevated predation, and species invasions near roads. The net effect is that, by virtue of their unique characteristics and abundance of ecologically specialized species, rainforests and their wildlife are exceptionally vulnerable to roads and other linear clearings.

Secondly, from a socioeconomic perspective, tropical rainforests are strongly concentrated in developing nations, many of which are experiencing further population growth, rapid economic development, and intense natural-resource exploitation. As a result, roads are running riot. For example, Brazil has just punched a 1200-kilometer-long highway into the heart of the Amazon (the BR-163) and is in the process of constructing another, 900-kilometer-long highway (the BR-319) that will cut into nearly

ROADS AND OTHER LINEAR INFRASTRUCTURE HAVE SERIOUS ENVIRONMENTAL IMPACTS ON NATURAL HABITATS WORLDWIDE, BUT TROPICAL RAINFORESTS SEEM SPECIALLY VULNERABLE.

FIGURE 1

Myriad species, such as this lemuroid ringtail possum (*Hemibelideus lemuroides*) from northern Queensland, Australia, are specialized for the dark, humid conditions of tropical rainforests (photo © Michael Trenerry).

NAME AND LOCATION*	SYNOPSIS OF IMPACT
EXISTING ROADS	
BELEM–BRASÍLIA HIGHWAY, BRAZIL	Paved in the 1960s, this 1500-km highway has spawned a 400-km-wide slash of deforestation across eastern Amazonia
CUIABÁ–PORTO VELHO HIGHWAY, BRAZIL	This 1500-km highway, funded by the World Bank, has promoted rampant forest loss in southwestern Amazonia
CUIABA–SANTARÉM HIGHWAY, BRAZIL	Visible as a "line of fire" at night, this recently paved highway cuts for over 1200 km into the heart of the Amazon
ECUADORIAN OIL ROADS	Roads associated with two 400-km-long oil pipelines have opened up much of Ecuadorian Amazonia to destructive colonization, with major impacts on indigenous groups
SAMLING ROAD, SARAWAK, MALAYSIA	This 300-km road, recently built by Samling Timber Corporation, is opening up northern Sarawak, Borneo to industrial logging
ANDAMAN TRUNK ROAD, ANDAMAN ISLANDS, INDIA	Running 420 km across four nearby islands, this highway promoted both massive deforestation and social upheaval for the indigenous communities of the islands
DOUALA–BANGUI ROAD, CAMEROON–CENTRAL AFRICAN REPUBLIC	Completed in 2003, this highway cuts 1400 km across the northwestern Congo Basin and has promoted massive logging, poaching, and forest loss
ROADS UNDER CONSTRUCTION OR PLANNED	
MANAUS–PORTO VELHO HIGHWAY, BRAZIL	This 900-km paved highway will link the nearly pristine central Amazon to major population centers to the south
TRANSOCEANIC HIGHWAYS, PERU–BOLIVIA–BRAZIL	Already hotspots of deforestation and frontier lawlessness, this triad of paved highways will link Brazil to the Pacific Ocean and lucrative export markets in China
TRANS–CONGO ROAD, DEMOCRATIC REPUBLIC OF CONGO	Funded by China, this 1600-km road will cut across the Congo Basin, from the southeast to northwest, providing access to rich mineral and timber resources
NORTH–SOUTH ECONOMIC CORRIDOR, INDOCHINA	This 1500-km highway will provide a direct link between aggressive timber importers in China and Laos, Cambodia, Thailand, and Myanmar, whose forests are rapidly shrinking
LEUSER ROAD PLAN, SUMATRA, INDONESIA	This network of 450 km of main roads and 1200 km of minor roads is likely to open up surviving forests in northern Sumatra to illegal logging, poaching, and deforestation
MAMBERAMO BASIN ROADS, PAPUA, INDONESIA	Spanning 1400 km, this China-funded road network will crisscross pristine forests in northwestern New Guinea

FIGURE 2

Roads to ruin. A sampling of the most environmentally destructive roads in the tropics and others imminently planned or under construction.

* Compiled from refereed publications, technical reports, and consultations with tropical researchers, environmental organizations, and conservation websites such as www.mongabay.com.

pristine forest. A triad of new highways is slicing across the Andes Mountains, from the Amazon to the Pacific. New road networks in Sumatra are opening up some of the island's last remaining forests to predatory loggers and hunters. A recent study found 52,000 kilometers of new logging roads in the Congo Basin (LaPorte *et al.* 2007). These are but a small sampling of the new roads and highways penetrating into the world's last tropical frontiers [Figure 2].

GLOBALIZATION AND ROADS

Economic globalization is playing an ever-bigger role in road expansion and tropical deforestation. Tropical forests are disappearing at an average rate of 10–13 million hectares a year (FAO 2005)—the equivalent of roughly 50 football fields per minute. While this rate has remained relatively constant over the past few decades, the underlying causes of deforestation have shifted dramatically—from mostly small-scale, subsistence-driven deforestation through the 1980s, to far more industrial-driven deforestation more recently (Geist and Lambin 2002; Rudel 2005).

Beginning around the end of the Second World War and continuing through the late 1980s, tropical deforestation was mostly a consequence of two factors. The first was explosive growth of the human population in developing nations (Myers 1993). From 1950 to 1990, for example, the populations of the three biggest tropical nations, Brazil, Indonesia, and the Democratic Republic of Congo, collectively rose by more than 250%, from 146 million to 368 million people (UN 2004). The second factor promoting deforestation was government policies for rural development, such as agricultural loans, tax incentives, forest-colonization programs, and rural-road construction (Rudel 2005). Such initiatives, especially evident in countries like Brazil and Indonesia (Fearnside 1997), promoted large influxes of colonists and shifting cultivators [Figure 3] into frontier areas and caused alarming forest loss.

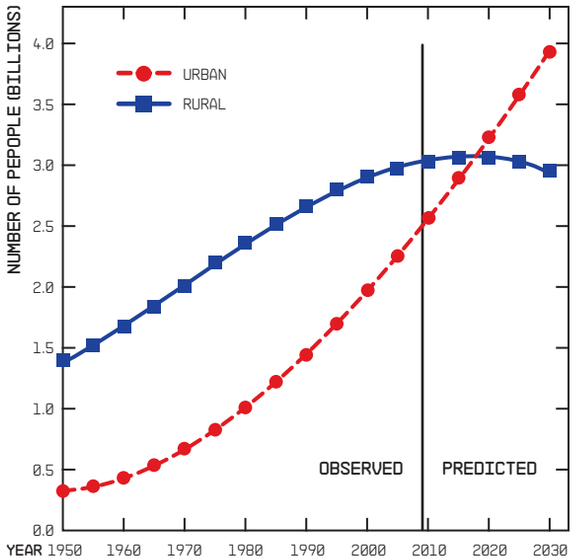
More recently, however, the impacts of rural peoples on tropical forests seem to be stabilizing. Although many tropical nations still have considerable population growth, strong urbanization trends (except in Sub-Saharan Africa) mean that rural populations are growing more slowly [Graph 1], and are even declining in some areas (UN 2004). The popularity of large-scale frontier-colonization programs has

also waned (Fearnside 1997; Rudel 2005). If such trends continue, they could begin to alleviate some pressures on forests from small-scale farming, hunting, and fuel-wood gathering (Wright and Muller-Landau 2006).

At the same time, globalized financial markets and a worldwide commodity boom are creating a highly attractive environment for the private sector. Under these conditions, large-scale agriculture—crops, livestock, and tree plantations—by corporations and wealthy landowners is increasingly emerging as the biggest direct cause of tropical deforestation (Rudel 2005; Nepstad *et al.* 2006a). In Brazilian Amazonia, for instance, large-scale ranching has exploded, with the number of cattle quadrupling, from about 20 to 80 million head, since 1990 (Smeraldi and May 2008). Industrial soy farming has also grown dramatically in Amazonia (Fearnside 2001). In Southeast Asia, expansion of industrial oil palm and rubber plantations has become a major driver of deforestation (Koh and Wilcove 2008). Surging demands for grains and edible oils, driven by rising standards of living in developing countries and the global thirst for biofuels, are also spurring these trends (Von Braun 2007; Scharlemann and Laurance 2008).

Road expansion and demand for new agricultural land often go hand in hand. In Brazil, for example, the powerful soy lobby has been a major proponent for the construction of new paved highways into the unexploited heart the Amazon. The lobby wants these highways so they can easily transport millions of tons of soy to the Amazon River, where it can then be exported internationally (Fearnside 2001). Other industrial activities, especially logging, mining, and oil or gas development [Figure 2], are also providing a key economic impetus for road building in tropical frontiers (Laurance 2001; Laurance *et al.* 2001; Asner *et al.* 2005; Finer *et al.* 2008).

Globalization is having another important impact on tropical deforestation. Historically, it is the nations with the highest population densities that have tended to lose the most forest (Wright and Muller-Landau 2006) and have the most threatened species (Sodhi *et al.* 2009). However, this relationship may be weakening because of international trade (Laurance 2007a; Butler and Laurance 2008). For instance, even a nation like Gabon, with a population density of fewer than five people per square kilometer on average, could lose much of its forest as China



GRAPHIC 1

Past and projected changes in rural and urban populations for developing nations, based on data from the UN Population Division. Projected changes are for a 'median' population-growth scenario (Adapted from Engelman 1998).

aggressively buys up huge stocks of the country's raw timber, mineral, and oil resources (Laurance *et al.* 2006a). Thus, globalization may increasingly de-link the relationship between local population density and environmental degradation, so that even sparsely populated nations can be rapidly exploited and deforested.

ROADS AND RAINFORESTS

Roads can have wide-ranging impacts on natural ecosystems. Some are a direct consequence of road building, maintenance, and vehicle traffic, whereas others—often the most devastating—are a result of greatly increased physical accessibility to the forest (see Laurance *et al.*, in press). Here I briefly summarize some the main effect of roads on rainforests.

PHYSICAL DISTURBANCES AND POLLUTION

In the tropics, as elsewhere, roads can seriously affect local soils, streams, and water quality (Trombulak and Frissel 2000). Roads are typically constructed using a cut-and-fill approach to help level local topography. Unless culverts are installed at frequent intervals, the filled areas impede drainage, especially in regions that receive heavy wet-season rains. This can cause flooding on the upstream side of the road that kills rainforest vegetation [Figure 4a]. On the downstream side of roads, water flow is often greatly impeded, causing streams to fail.

Road-cuts and local sand- and gravel-quarrying operations are major sources of erosion [Figure 4b], with each hectare bleeding from 35–500 metric tons of sediments into nearby

FIGURE 3

The changing drivers of tropical deforestation: Small-scale cultivators versus industrial road expansion in Gabon, central Africa (photos: William Laurance).

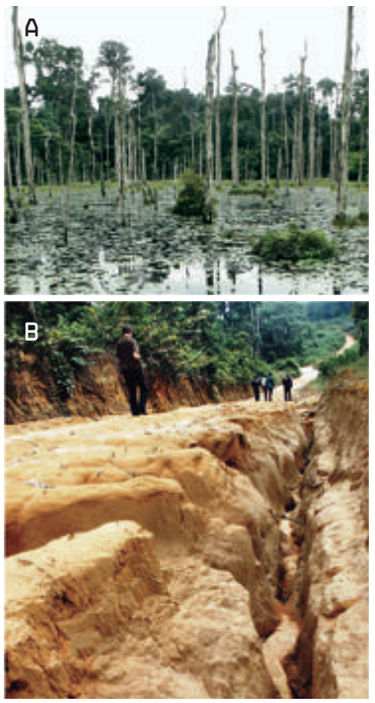


FIGURE 4

Damage from road works: **(A)** forest flooding and **(B)** heavy erosion along roads in the Congo Basin (photos: William F. Laurance).

streams each year (Bruijnzeel 2004). These sediments degrade water quality and clog up streambeds, killing many fish, aquatic insects, and other stream-dwelling wildlife.

Finally, roads and vehicles can be a chronic source of pollutants. Dust, heavy metals, nutrients, ozone, and organic molecules are elevated within 10–200 meters of roads (Trombulak and Frissel 2000; Pratt and Lottermoser 2007a). Chemical pollutants and nutrient runoff from roads are especially harmful to nearby streams and wetlands, with pulses of waterborne pollutants entering aquatic ecosystems when rainfall is heavy (Pratt and Lottermoser 2007b). Such contaminants can have wide-ranging effects; for example, many aquatic insects are acutely sensitive to water pollution, waterborne nutrients can promote blooms of algae that deplete the water of life-giving oxygen, and heavy metals are toxic to many animal species.

EDGE AND BARRIER EFFECTS

A road slicing through a rainforest is a highly artificial environment. Forests along road clearings are typically drier, hotter, and windier than are forest interiors. These changes can kill some trees near the clearing from heat stress or windthrow, and the higher light levels along roads promote a proliferation of disturbance-loving vines and weeds (Murcia 1995; Laurance *et al.* 2002b; S. G. Laurance 2004).

Being ecologically specialized for dark, humid conditions, many rainforest animals tend to avoid the foreign disturbance created by roads and their abrupt forest edges. Examples include strictly arboreal species, such as certain monkeys, sloths, and possums; understory bats specialized for flying in dense, cluttered environments; understory birds [Figure 5] with a strong psychological avoidance of clearings; and larger mammals that shun humans or traffic noise near roads (Goosem 2001, 2007; Develey and Stouffer 2001; S. G. Laurance *et al.* 2004).

For rainforest specialists, roads can seriously impede their natural movements, dispersal, and gene flow, leading to population isolation and fragmentation (Laurance *et al.*, in press). Such deleterious effects are likely to be compounded as road density increases, with road-dominated landscapes becoming increasingly hostile terrain for rainforest specialists. In concert with other impacts, such as hunting or road-kill, roads can have a serious impact on population survival.

ROAD-KILL AND HUNTING

Many animals are killed along roads from collisions with vehicles [Figure 6] (Goosem 1997, 2007) or from human hunting or trapping near roads. In terms of population survival, chronically elevated mortality is most serious for species that are rare, range over large areas,

FIGURE 5

Many understory birds, such as this black-headed antbird (*Percnostola rufifrons*) from central Amazonia, avoid forest clearings and edges (photo: Susan Laurance).

or have low reproductive rates, such as predators and larger-bodied mammals and birds (Bennett and Robinson 2000).

Road-kill from vehicles is limited to the road surface itself. Hunting by humans, however, can create zones of elevated mortality and animal avoidance within at least 5–10 kilometers of roads, and possibly much further for wide-ranging species (Lahm *et al.* 1998; Laurance *et al.* 2006b, in press; Blake *et al.* 2007). Populations of the African forest elephant, for example, appear to be depressed up to 50 kilometers from roads (Blake *et al.* 2008). Notably, the traits that predispose a species to road-kill, such as slow movement, poor eyesight, and forest edge-favoring behavior, are very different from those, such as large body size, gregarious social systems, conspicuous calls or displays, and the use of regular pathways, that predispose them to hunting or trapping by humans (Laurance *et al.*, in press). Thus, roads affect a broad spectrum of species with widely varying characteristics.

FIGURE 6

Many rainforest animals, such as this Malayan tapir (*Tapirus indicus*), are killed by collisions with vehicles (photo © Lan Ching Fong, World Wide Fund for Nature-Malaysia).

INVASIONS OF EXOTIC SPECIES

Many exotic species love roads, which provide avenues for invading forests. Among others, such invaders include little fire ants (*Wasmannia auropunctuta)*, exotic earthworms, non-rainforest vertebrates, fungal die-back (*Phytophthora* species), and myriad weed species (Dawson and Weste 1985; Walsh *et al.* 2004; Brown *et al.* 2007). Some of these invaders are having major impacts on tropical ecosystems. Little fire ants, for instance, are proliferating throughout African rainforests around 60 times faster along logging roads than through undisturbed forest, and kill or blind native species such as monkeys, apes, leopards, and insects (Walsh *et al.* 2004). Invasions can occur with surprising rapidity; for example, non-rainforest frogs, leafcutter ants, lianas, and exotic weeds are already penetrating into remote areas of the Amazon, using the verges of recently constructed roads as invasion corridors (Gascon *et al.* 1999).

Road-borne invaders affect people too. In Ecuador, for example, human enteric pathogens are 2–8 times higher in villages near roads than in more remote areas (Eisenberg *et al.* 2006). Increased incidences of dengue fever (Dutta *et al.* 1998), malaria (Hayes and Ferraroni 1981), and HIV (Carswell 1987) have been reported in people living near roads in India, Brazil, and Uganda, respectively. By accelerating invasions of novel and potentially lethal pathogens, roads penetrating into remote frontiers also threaten indigenous groups attempting to live with limited or no contact with outsiders. The Surui Amerindians of Brazilian Amazonia, for instance, have been driven to the edge of extinction by roads and the new infectious diseases they bring (Butler 2009).

HUMAN INVASIONS

In the tropics, roads greatly facilitate invasions of hunters, miners, colonists, and land speculators—a phenomenon dubbed the "Pandora's Box Effect" (Laurance 1998). In Brazilian Amazonia, for example, ~95% of all deforestation and fires occur within 50 kilometers of highways or roads [Figure 7] (Laurance *et al.* 2001). In Suriname, most illegal gold-mining operations are located near roads (Laurance 2008), whereas in tropical Africa, hunting intensity increases so sharply near roads that it strongly affects the large-scale distribution of forest elephants, buffalo, duikers, primates, and other exploited species (Lahm *et al.* 1998; Laurance *et al.* 2006b; Blake *et al.* 2007, 2008). Roads can greatly increase trade in bushmeat and wildlife products; for example, eight killed mammals were transported per hour on average along a single highway in Sulawesi, Indonesia (Lee *et al.* 2005).

Many formerly remote tropical regions, such as the Amazon (Laurance *et al.* 2001), Congo

FIGURE 7

Roads promote forest destruction.

(A) Close association between frontier roads and deforestation in Brazilian Amazonia (image from NASA).

(B) Clustering of forest fires (red) and deforestation (yellow) near roads in northern Bolivia in 1997 (image from Marc Steininger, Conservation International).

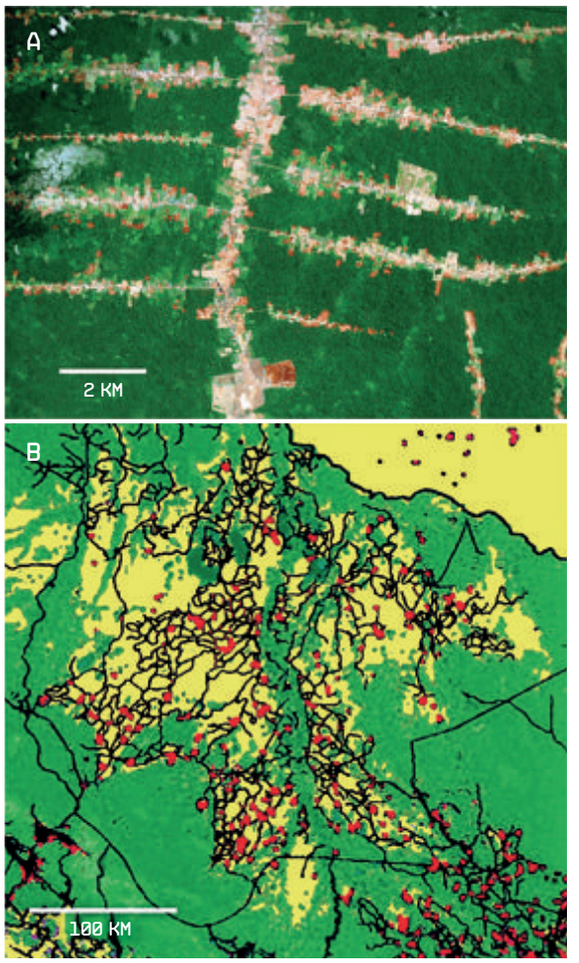
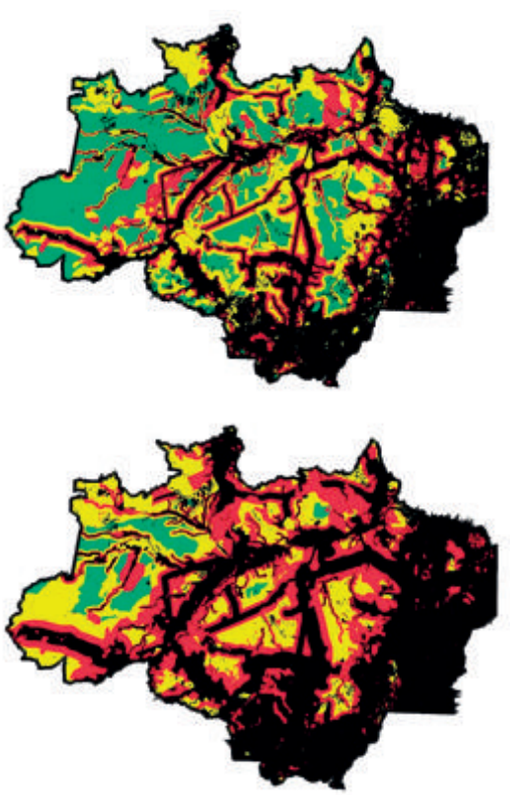


FIGURE 8

As illustrated by these "optimistic" (above) and "non-optimistic" (below) scenarios, forests in Brazilian Amazonia will be profoundly affected by existing and planned roads and paved highways. Both models show projected forest cover for the year 2020. Areas in black are projected to be deforested or severely degraded, whereas those in red, yellow, and green will be moderately degraded, lightly degraded, and pristine, respectively, according to computer models (from Laurance et al. 2001).



Basin (LaPorte *et al.* 2007), New Guinea (Shearman *et al.* 2009), and Borneo (Curran *et al.* 2004), are now being assailed by expanding road networks, particularly from industrial timber operations and oil, gas, and mineral projects. Paved highways, which provide year-round access to forests, typically have much greater impacts on forests and wildlife than do unpaved roads (Laurance *et al.* 2002a; Fearnside 2007; Soares-Filho *et al.* 2006), which tend to become inaccessible in the wet season.

By opening up new lands for colonization, proliferating frontier roads can also depress land prices across a region (although land prices near the road itself will typically rise because of greater access to markets). Lower land prices create a disincentive for landowners to invest in more-sustainable land uses (Laurance *et al.* 2001). Agriculture in the Amazon, for instance, is overwhelmingly dominated by fire-based methods, such as slash-and-burn farming and forest burning for low-density cattle ranching and charcoal production. These fire-based methods deplete soil nutrients so badly that farmlands are often abandoned after a few years, and also promote wildfires during periodic El Niño droughts (Cochrane 2003). Were land not so cheap and readily available, landowners would have a greater incentive to invest in more sustainable and profitable farming methods, such as agroforestry, tree plantations, and fruit crops, which are not fire-based (Laurance *et al.* 2001).

REDUCING THE IMPACTS OF ROADS

Measures to diminish the environmental impacts of roads fall into two categories: local strategies to reduce road impacts, and regional efforts to limit the expansion of roads into ecologically sensitive areas.

LIMITING ROAD EXPANSION

In simplest terms, roads can be thought of as the enemies of rainforests. Although roads are often an integral part of economic development, poorly planned roads can lead to massive forest disruption. In particular, roads that penetrate into remote frontier regions [Figure 2] should be avoided wherever and whenever possible. Paved highways are particularly damaging as they tend to spawn networks of secondary roads that dramatically increase the spatial scale of their impact (Perz *et al.* 2008); for example, the Belem-Brasília Highway, completed during the early 1970s, has now evolved into a 400

FIGURE 9

Logging trucks queue up at a highway in Malaysian Borneo (photo by Jeffrey Vincent).

kilometer-wide swath of forest destruction and secondary roads across the eastern Brazilian Amazon (Laurance 1998). In efforts to project the future of the Amazon ecosystem [Figure 8], the locations of roads are the greatest single factor influencing expected spatial patterns of forest loss, fragmentation, and degradation (Laurance *et al.* 2001; Soares-Filho *et al.* 2006).

Large-scale efforts to expand regional highway networks in South America, South and Southeast Asia, and Sub-Saharan Africa are cause for great concern. Across all of these regions, perhaps the most notable trend in recent years is growing investment by China in frontier roads that will sharply increase access to mineral, oil, and timber resources. Maintaining large, roadless areas of intact forest should be among the highest priorities for regional conservation managers.

MANAGING TIMBER OPERATIONS

Industrial logging is currently occurring in about 28% of the world's tropical forests (Asner *et al.*, in press), and is probably the greatest single driver of road expansion in forest frontiers. In the tropics, nearly all logging is selective, with loggers using bulldozers and other heavy equipment to extract a limited number of trees from the forest (typically 1–10 trees per hectare). However, depending on harvest intensity, anywhere from 20–80% of the overhead forest-canopy cover can be destroyed, with logging tracks and roads proliferating throughout the forest and causing substantial soil damage, erosion, and fragmentation of the understory vegetation (Fimbel *et al.* 2001).

Many forests in the Asia-Pacific region have already been severely depleted by loggers [Figure 9]. Surviving forests in the Amazon, New Guinea, and Congo Basin are now experiencing explosive timber expansion, with the Congo alone having at least 52,000 kilometers of recently created logging roads (LaPorte *et al.* 2007). In the Amazon, forests penetrated by roads from logging operations are about 400% more likely to be deforested than are unlogged forests (Asner *et al.* 2006).

Most logging in the tropics suffers from poorly planned and excessive road building (Putz *et al.* 2000). Efforts to reduce logging damage focus strongly on roads, with measures such as minimizing road works via careful pre-harvest planning, restricting roads wherever possible to flatter slopes and ridgelines, limiting widths of logging roads, minimizing stream crossings to reduce damage to streamside vegetation, and prohibiting logging during wet periods to reduce soil erosion and stream sedimentation (Fimbel *et al.* 2001). In addition, greater attention should focus on closing logging roads after harvest operations (such as by destroying key bridges or otherwise rendering the road impassable) to reduce post-logging invasions of forests by illegal colonists, hunters, and miners.

From an environmental perspective, some schemes for logging expansion appear especially alarming. In Brazilian Amazonia, for example, plans are afoot to log dozens of widely scattered National Forests—many located in remote, largely pristine areas—that could ultimately span over 50 million hectares (Verissimo *et al.* 2002). The vast network of new roads

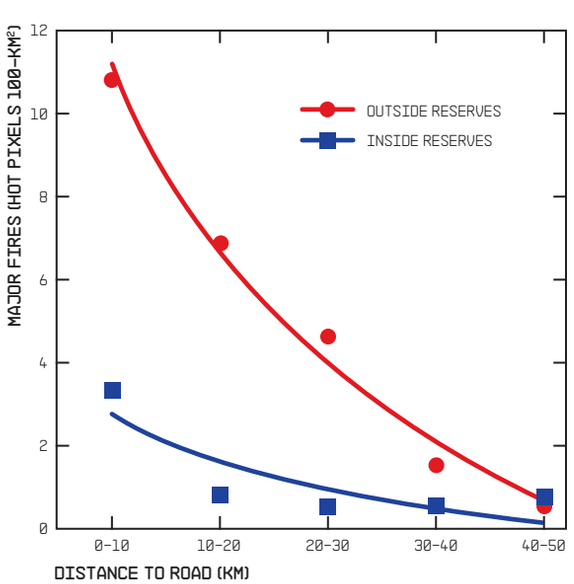
GLOBALIZATION MAY INCREASINGLY DE-LINK THE RELATIONSHIP BETWEEN LOCAL POPULATION DENSITY AND ENVIRONMENTAL DEGRADATION, SO THAT EVEN SPARSELY POPULATED NATIONS CAN BE RAPIDLY EXPLOITED AND DEFORESTED.

required for such an enterprise dramatically increase forest invasions, hunting, and land speculation in frontier areas. Similarly, efforts are underway to open up some of the last surviving forests in northern Sumatra to industrial logging [Figure 2].

REDUCING HUMAN INVASIONS

When roads in frontier areas cannot be avoided, unplanned forest loss and invasions by illegal colonists can be reduced by creating protected areas along the road route in advance of road expansion (Fearnside 2006; Nepstad *et al.* 2006b). In the Brazilian Amazon, for example, forest destruction has been more severe along the Cuibá-Santarém Highway, which had few protected areas in place prior to road construction, than along the Porto Velho-Manaus Highway, where 13 protected areas were established before or during road construction (although the latter is still incompletely paved and could suffer further in the future; Butler 2008a). More generally, forest fires are far less frequent near roads in Amazonian protected areas and indigenous lands than near roads in unprotected forest [Graphic 2] (Adeney *et al.* 2009).

Another strategy to reduce human invasions is establishing railroads rather than roads in frontier areas. Incursions into forests can be partially controlled because trains stop only at designated locations, and these can be situated strategically to limit invasions of environmentally sensitive areas. In Brazil, for example, a railroad has been advocated instead of the Manaus-Porto Velho Highway, which could greatly increase forest colonization in central Amazonia (Butler 2008b).



GRAPHIC 2

Incidence of human-lit forest fires at varying distances from roads, comparing areas inside versus outside protected areas in Brazilian Amazonia (Adapted from Adeney *et al.* 2009).

PROPERLY ASSESSING ROAD IMPACTS

Among the most serious hindrances to effectively limiting and mitigating roads is that, in many developing nations, environmental-impact assessments (EIAs) of proposed roads focus solely on the road route itself, ignoring the impacts of roads on forest invasions, hunting, and secondary-road expansion (Laurance 2007b). In Brazil, for instance, EIAs of major new Amazonian highways were often confined to a narrow swath along the road route itself, sometimes recommending such paltry mitigation measures as "helping" animals to move from the planned route before road building (Fearnside 2006). In other cases, such as for certain mines, hydroelectric dams, and other large developments, the EIA focuses on the project itself but ignores the impact of the roads it will inevitably spawn (Reid and Souza 2005). New roads will continue to be major drivers of forest disruption so long as the EIA process is so fundamentally flawed.

ROAD-DESIGN STRATEGIES

In nature reserves and other areas of high conservation significance, various measures can be used to minimize road impacts. The most important principle is that road density should be minimized, and roadless core-areas maximized, to sustain disturbance- and hunting-sensitive wildlife and reduce exotic-species invasions (Peres and Lake 2003; Blake *et al.* 2008). Flooding from road works can be minimized by installing large culverts at regular intervals under roads. Edge and barrier effects can be limited by minimizing road widths so that some forest-canopy connectively is maintained and allowing secondary growth, which provides a partial buffer against harmful edge effects, to proliferate along forest margins (S. G. Laurance 2006). Bridges over watercourses that include both a corridor of unflooded vegetation and natural streambed are especially effective for allowing animal movements, but culverts can also provide avenues for movements of smaller animals (Goosem 2007).

CONCLUDING REMARKS

Efforts to promote road expansion in the tropics are perhaps the most striking example of how globalization and regional economic integration in developing nations can be directly at odds with nature conservation. Economists and infrastructure planners typically see frontier road expansion in a positive light, whereas those

alarmed by rapid deforestation perceive it in opposite terms, given the logistical challenges, expense, and near-futility of frontier governance once the roads go in.

All is not hopeless, however. Because frontier roads play a key role in promoting tropical deforestation and global carbon emissions (see Lovejoy, this volume), forest carbon-trading initiatives could increasingly focus on limiting and mitigating such roads. For example, such funds could potentially be used to help plan and minimize regional road works, establish protected areas in advance of road establishment, regulate road access, promote railroads rather than roads where feasible, and close down the environmentally most destructive roads (Laurance *et al.*, in press).

Globalization and rapid economic development are leading to a massive proliferation of destructive roads in the world's last surviving tropical frontiers. Actively limiting these frontier roads, I assert, is by far the most realistic, cost-effective approach to promoting the conservation of tropical nature and its crucial ecosystem services. As Pandora quickly learned, it was far harder to thrust the evils of the world back into the box, than to simply not open it in the first place.

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