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The Amazon's Vicious Cycles

Drought and Fire in the Greenhouse

Ecological and Climatic Tipping Points of the World's Largest Tropical Rainforest, and Practical Preventive Measures

A report to the World Wide Fund for Nature (WWF)
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Executive Summary

"Amazon" evokes in our minds vast rainforest, the world's largest river system, the profusion of life, cultural and biological diversity intermingled and interdependent. Locked away in the compounds of its plants and animals are as yet undiscovered cures to diseases and components of the molecular technology that we will need to live more lightly on this planet. And in its far reaches live indigenous societies that have never come face-to-face with modern outsiders. But "Amazon" is taking on a new meaning. It has become a global symbol of humanity's dependence upon natural ecosystems. It shapes climate as we know it today, and may be threatened by a world climate that is increasingly warm and erratic. The aim of this report is to explore the relationship between the Amazon, climate, and the changes in this relationship that are underway as a result of forest destruction and the release of heat-trapping gases into the atmosphere. It seeks to interpret the best information available to determine how close we are to a point of no return for a major forest "dieback" in the Amazon, and to identify some steps that might be taken to counter this process.

The intimate link between the Amazon forest and climate

1) The Amazon forest complex is intimately connected to the world's climate. First, it influences climate by acting as a giant consumer of heat close to the ground, absorbing half of the solar energy that reaches it through the evaporation of water from its leaves[1]. Second, it is a large, fairly sensitive reservoir of carbon that is leaking into the atmosphere through deforestation, drought, and fire, contributing to the build up of atmospheric heat-trapping gases that are the cause of global warming. Third, the water that drains from these forests and into the Atlantic Ocean is 15-20 per cent of the world's total river discharge, and may be enough to influence some of the great ocean currents that are, themselves, important regulators of the global climate system. *Amazon forest conservation will be necessary to stabilize the world's climate.*

2) The Amazon is at the cusp of a period of dramatic transformation through climate change. Global warming will probably reduce rainfall in eastern Amazonia by more than 20 per cent and increase the overall Amazon region's temperature by more than 2°C, and perhaps by as much as 8°C, by the end of the century if society fails to make the deep cuts in greenhouse gas emissions that are needed if we wish to avoid dangerous climate change. The drying will be most severe in the eastern Amazon. This drying and heating trend may be reinforced by the large-scale die-back of eastern Amazon rainforests as they are replaced by savanna-like and semi-arid vegetation. *Stabilization of the world's climate will be necessary to conserve Amazon forests.*

Point of no return may be closer than we think

1) Many changes underway in the Amazon today could lead to extensive conversion and degradation of Amazon forests over the next 15-25 years, well ahead of the late-century forest dieback predicted by some models. Current trends in agriculture and livestock expansion, fire, drought, and logging could clear or severely damage *55 per cent of the Amazon rainforest by the year 2030.*

2) *Extensive degradation of forest could be speeded through the synergistic influence of several vicious feedback loops that exist within and among the ecosystems and climate of the Amazon region.* If the Amazon forest tipping point is reached, the prospect of conserving the Amazon rainforest will be greatly diminished, while the loss of biodiversity and the emission of greenhouse gases from the region will increase.

3) The *ecological tipping* point will be reached when fire-resistant native forests are degraded into fire-prone brush through repeated forest damage from drought, logging, or fire. This tipping point is favoured by vicious cycles within the Amazon fire regime. Forests that burn are more susceptible to further burning because fire-induced tree death allows more sunlight to reach the forest interior, drying dead leaves and branches on the forest floor. Forest invasion by flammable grasses, ferns, and bamboo following fire reinforces the vicious cycle of burning by increasing the amount of fuel on the forest floor. The ecological tipping point is favoured by fire-dependent agricultural practices

[1] Much of the energy trapped in water is released when the vapour condenses to form clouds and rain, and this is one of the major engines of global atmospheric circulation.

that provide abundant ignition sources, such as extensive cattle ranching and swidden (slash-and-burn) agriculture.

4) The climatic *tipping point* is reached when deforestation; smoke; sea surface temperature anomalies, such as El Niño episodes; and global warming itself inhibit rainfall on a regional scale. This climatic tipping point is self-perpetuating because it favours the degradation and burning of forests that reduces the release of water vapour and increases smoke emission to the atmosphere, both of which suppress rainfall. Inhibition of rainfall driven by deforestation appears to become stronger as forest clearing exceeds 30 per cent.

5) *Amazon deforestation may accelerate* in the future through two major trends. First, the growing world demand for soybeans, biofuel, and meat are increasing the profitability of agriculture and livestock production in the Amazon, thereby strengthening the incentive for farmers and ranchers to convert their legally-required forest reserves to agriculture and pasture. Second, the risk of accidental fire discourages landholders from investing in fire-sensitive tree crops, forest management, or forage improvement as it reinforces a dependence on extensive cattle ranching (with low grazing densities) and swidden agriculture that, in turn, further increase the risk of accidental fire.

6) *These synergies among Amazon forests, economies, and climate favour large-scale forest dieback in the next 15 to 25 years.* In a dieback scenario, forest fires are increasingly common, fire-dependent extensive cattle ranching and swidden agriculture provide an expanding frontier of ignition sources, and regional droughts are more frequent because of lowered transpiration and greater smoke production. Growing demands for soybeans, biofuels, and meat increase the profits to be made from deforestation.

7) *Large-scale degradation of Amazon forests could speed the global climatic disruption, influencing the rainfall in far-flung places around the planet.* The predictions for the period from now to 2030 described in (1) would release 15-26 billion tonnes of carbon to the atmosphere equivalent to 1.5 to 2.6 years of current worldwide carbon emissions. With further destruction of the Amazon forest, changes in rainfall are anticipated in other places around the world. Some models indicate that rainfall could decline in India and Central America, and that rainfall during the crop growing season may decline in the grain belts of Brazil and the United States of America.

8) *Current economic trends and climate change at regional and global scales could also destroy important ecoregions of the Amazon region, such as the Maranhão babaçu forest, the Marañon dry forest, and the cloud forests of Bolivia.* Given current trends, many species of animal, including several primates, will lose more than 80 per cent of their primary forest habitat over the next few decades.

Chances for a turnabout

1) Several *processes and virtuous feedback loops could prevent the Amazon from reaching these tipping points* and form the foundation of a bold new Amazon conservation strategy.

2) The *virtuous ecological feedback loop* is the tendency of forests to rapidly regrow when released from periodic burning. Most of the degraded lands of the Amazon will return to closed-canopy forest if protected from fire, recovering the rainfall stabilization functions of primary forests within 15 years. With each year of fire-free recovery that goes by, the flammability of the forest declines and the amount of rain cloud forming vapour that is pumped into the atmosphere increases.

3) In the *virtuous climate feedback loop* the recovery of forest water vapour production (transpiration) over large landscapes through forest regrowth and through the establishment of tree crops together with the reduction of fire leads to greater rainfall. This, in turn, facilitates forest recovery and further reduction in fire incidence

4) Two *virtuous economic feedback loops* involve changes in landholder behaviour that can reduce the incidence of fire and increase compliance with landuse legislation. First, commodity markets are requiring greater social and environmental performance of farmers and livestock producers who, in turn, are responding through campaigns to increase the legality and the socio-environmental performance of their farms and ranches. Peer-to-peer enforcement and a common goal of greater access to lucrative commodity markets is increasing investments in fire prevention, in the restoration of riparian zone forests, and in compliance with require-

ments for private land forest reserves. Second, as clusters of landholders succeed in establishing fire-sensitive tree crops, forest timber management systems, and improved forage on their land, they will use fire as a management tool less and invest more in fire prevention. These landholders will also encourage their neighbours to prevent accidental fire perhaps until a turning point is reached beyond which fire-using producers become a diminishing minority from entire landscapes.

5) *Sustainable timber management involving "reduced impact" logging techniques represents an important economic alternative* to deforestation-dependent farming and ranching. Reduced impact techniques permit logging companies to selectively harvest timber with only minor increases in forest susceptibility to fire, increasing the feasibility of repeated harvests in the future.

6) *Merely implementing existing land-use policies and programmes within the Brazilian Amazon and extending these policies and programmes to other Amazon countries could reduce deforestation by half.* For example, the Amazon Region Protected Areas (ARPA) programme and participatory regional planning processes in preparation for infra-structure investments have already contributed to the creation of 23 million hectares of new reserves in 2004 and 2005 alone that have reduced the availability of land on the Brazilian Amazon frontier, lowering deforestation rates.

7) *There is still time to lower the risk of widespread Amazon forest degradation and the acceleration of global warming that it would stimulate.* All opportunities to govern Amazon frontier expansion must be seized. One of the most promising approaches to the large-scale conservation of Amazon forests are the proposals, within the UN Framework Convention on Climate Change, to reduce emissions from tropical forests that give UNFCCC signatories a new and powerful incentive to invest in forest preservation.

Introduction

The Amazon forest influences life on Earth through several processes, many of which we are still trying to fully understand. This forest is one of the world's greatest air conditioner, transforming half of all the solar energy that reaches it through the evaporation of huge amounts of water from its leaves and other surfaces – approximately 8 trillion tonnes each year (Salati and Vose 1984). The release of this water vapour to the atmosphere is crucial to the formation of the cumulus clouds that, in turn, sustain the forest with rainfall. But the energy absorbed by Amazon forests has influences that extend around the world through linkages called climatic "teleconnections". According to one modelling experiment, farmers of the grain belt in the United States of America's Midwest and Brazil's breadbasket on the central plains of South America may find that their growing season rainfall declines as Amazon forests are converted to cattle pastures, while other changes in rainfall might be felt in such far-flung places as India, the western Pacific, and Central America (Werth and Avissar 2002, Avissar *et al*. 2005). The 7 or 8 trillion tonnes of water that flow through the mouth of the Amazon River into the Atlantic Ocean each year represent 15-20 per cent of the world's total river discharge of freshwater into the oceans. Could changes in this enormous river discharge influence the giant ocean currents that move energy around the planet and that help create the climate that we know today? Some scientists believe they could, but we simply don't know the answer.

Our lives are also connected to the well-being of the Amazon forest through its role as a storehouse of carbon – the element that is driving global warming through its release to the atmosphere as carbon dioxide, when combined with oxygen through burning or respiration, or methane, when combined with hydrogen. The trees of the Amazon contain 90-140 billion tonnes of carbon (Soares *et al*. 2006, Saatchi *et al*. 2007), equivalent to 9 to 14 years of current global, annual, human-induced carbon emissions – estimated in 2007 at approximately 10 billion tonnes per year (Canadell *et al*. 2007). The prospect of slowing global warming and keeping global average temperatures from rising no more than 2°C will be very difficult if emissions of carbon from tropical forests worldwide, and the Amazon in particular, are not curtailed sharply in the coming years (Gullison *et al*. 2007). This carbon is leaking out of the Amazon at the rate of about 0.2 to 0.3 billion tonnes of carbon each year – the result of forest conversion to cattle pastures and other agriculture in the Brazilian portion of the Amazon alone (Houghton *et al*. 2000, Fearnside 1997), and this number can double when severe drought increases the risk of forest fire (Nepstad *et al*. 1999a, Alencar *et al*. 2006). When all Amazon countries are combined, carbon emissions from this region may reach 0.4 to 0.5 billion tonnes per year even without considering emissions from forest fire[2].

Beyond its role as a giant, somewhat leaky reservoir of potential greenhouse gas emissions, the Amazon forest is home to one out of every four or five mammal, fish, bird, and tree species in the world (Dirzo and Raven 2003). More than 300 languages and dialects are spoken by the indigenous human populations of the region, including several populations that have never been contacted by outsiders.

The ecosystems and biodiversity of the Amazon may be threatened by global warming through a late-century, climate-driven substitution of forests by savanna-like and semi-arid vegetation in what has been called the Amazon forest "dieback" (Cox *et al*. 2000, 2004, Nobre *et al*. 1991, Oyama and Nobre 2003). However, these climate-vegetation simulations do not include land-use change, or the synergistic effects of land-use change and near-term regional climate change on the Amazon fire regime. Could accelerating forest-substituting and forest-damaging economic activities interact with regional climate change to replace or degrade a large portion of the Amazon forest system over the next two decades? What would be the regional and global impact of large-scale forest replacement by agriculture and livestock combined with forest degradation through logging, fire, and drought? And what counteracting trends could prevent the forest dieback looming on the horizon? These questions are the focus of this report. It reviews the current evidence of "tipping points[3]" in the Amazon's ecological and climatic systems, and describes some of the processes that could help the world avoid them.

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[2] Unpublished estimates that are described in a separate WWF report on livestock and agriculture in the Amazon.

[3] The "tipping point" refers to the moment at which a trend or social behaviour pattern crosses a threshold and suddenly begins to spread rapidly (Grodzins 1958, Schelling 1971, Granovetter 1978). This concept has been commonly used in epidemiology to describe the spread of disease, based on the concept that small changes will have little or no effect on a system until a critical mass is reached, at which point a small change "tips" the system and a large effect is observed. A similar concept of resilience has been developed to describe the capacity of a system to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes (Holling 1973, Gunderson and Holling 2002, Gunderson et al. 2002).

Drought, fire, and the ecological tipping point

Most forests of the Amazon are highly resistant to burning. Pour some kerosene on the dry leaves and branches of the forest floor during the peak of the dry season, ignite it, and watch the fire go out. This high resistance to burning is well understood by Amazon landholders, who ignite their fields and pastures with impunity because they know that the forests that surround them will act as giant firebreaks, putting out the fires if they escape (Nepstad *et al*. 1999b). In 1985, we learned that Amazon forests have succumbed to fire in the past. Robert "Buck" Sanford and collaborators presented the ages of charcoal fragments found in the soils of several Amazon forests dating back 6,000 years (Sanford *et al*. 1985). Anthropologist Betty Meggers expanded upon this important finding with additional charcoal data and other lines of evidence indicating that large areas of Amazon forest have burned at 400-700 year intervals over the last two millennia, and that these fires appear to have been associated with severe drought episodes (Meggers 1992). Today, the Amazon is facing much greater climatic drivers of severe drought episodes superimposed upon human transformations of Amazon vegetation.

During the last half century, one of the major ecological transformations of the Amazon region has been a shortening of the period between forest fires as humans have transformed forested landscapes. Instead of centuries between events, some forests are catching fire every 5-15 years (Cochrane *et al*. 1999, Alencar *et al*. 2006). And with every new burn, the forest becomes more susceptible to a subsequent fire. The ecological tipping point of Amazon forests is reached when they become so flammable that frequent periodic burning is virtually inevitable. To understand this ecological tipping point, we must understand the secret of Amazon forests' remarkable resistance to fire, and how disturbance can lower this resistance. To catch fire, the fuel layer of an Amazon forest – dead leaves and branches lying on the ground – must dry sufficiently to burn. This level of drying is very rare in tall, mature tropical forests because of the high level of humidity of the air. During most nights of the year, even after several consecutive weeks with no rainfall, humidity is so high that the air becomes saturated with moisture as it cools, and the fine fuel layer absorbs some of this moisture. As long as the fuel layer is shaded by a dense leaf canopy 30-45m above the ground, it rarely dries sufficiently to be ignited (Uhl and Kauffman 1990).

And therein lies the problem. In large parts of the Amazon Basin, reckless selective logging, drought, and fire itself are thinning the forest canopy, allowing more and more sunlight to penetrate to the fine fuel layer on the floor of the forest. Trees killed or removed by loggers (Nepstad *et al*. 1999a, Asner *et al*. 2005), trees killed by drought, and trees killed by fire open up the leaf canopy to the powerful rays of the equatorial sun, drying out the fine fuel layer on the ground. And with the greater sunlight in the forest interior, light-demanding plants that further increase forest flammability can become established. Although still a rare occurrence in the Amazon, highly-flammable grasses, ferns, and bamboo can become established in the forest understory, greatly increasing forest susceptibility to fire. When these damaged forests catch fire, more trees die and the invasion by grasses, ferns, and bamboos continues in a vicious feedback loop (Figure 1).

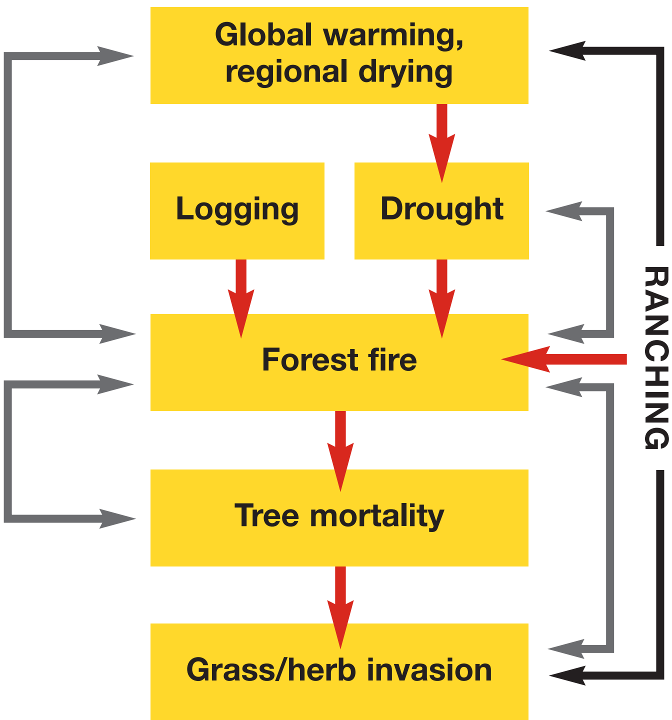


Figure 1: Diagram of the processes and interactions that push Amazon forests beyond their ecological "tipping points". This tipping point is reached when the forest's dominant organisms – its giant canopy trees – die from fire, drought, or logging, giving way to a flammable thicket of vegetation in the understory. Although still a rare occurrence in the Amazon, this human-driven process of forest degradation can be exacerbated through invasion by fuel-rich, flammable grasses, ferns, and bamboo.

Large-scale tree death from drought is a surprisingly rare event, but is critical to understanding how small changes in rainfall could push big areas of Amazon forest beyond their ecological tipping points. One of the great ecological puzzles of the Amazon forests is their ability to withstand severe seasonal drought with no visible signs of drought stress. Indeed, some researchers have reported satellite evidence of an early-dry season "greening up" of the Amazon forest canopy [Saleska *et al*. 2007, Myneni *et al*. 2006], although field measurements of this phenomenon are tenuous. Nearly half of the forests of the Amazon are exposed to seasonal drought for 3-5 months duration when monthly rainfall totals only 0-3 centimeters (Nepstad *et al*. 1994, 2004)[4]. Slowly, we are learning that these remarkable ecosystems have evolved mechanisms for maintaining lush, green leaf canopies through periods with little rainfall. The most important adaptation appears to be the deep (>10m) rooting systems of many Amazon forest trees that enable them to absorb water stored deep in the soil, as shallow soil moisture is gradually depleted during periods of little rainfall (Nepstad *et al*. 1994; 2004; 2007, Bruno *et al*. 2006; Hodnett *et al*. 1995). During the dry season, 75 per cent of the water released to the atmosphere through leaf "transpiration" is absorbed from greater than 2m depth in the soil (Nepstad *et al*. 1994). More recently it has been discovered that Amazon trees absorb substantial amounts of moisture from the dew that forms on their leaves during the dry season (Cardinot 2007).

Amazon forest drought tolerance has its limits, however, and it is in understanding these limits that we begin to realize how close these ecosystems are to their tipping point. A seven-year experiment was recently conducted to identify the level of drought stress beyond which Amazon forests would begin to "fall apart" through tree mortality. Rainfall was reduced by one third for five consecutive years in a one-hectare forest plot using 5,600 plastic panels placed above the soil (Nepstad *et al*. 2002). During the third year of the experiment, a drought threshold was reached. The forest's giant canopy trees began to die as they ran out of water in the upper 11m of soil (Nepstad *et al*. 2007). Trees representing 10 per cent of the total weight of all the trees in the forest died in the course of a single year. It appears that even these remarkable, deeply-rooting, giant trees succumb to drought and die if they cannot absorb enough water from the soil to supply their leaves with new water to replace that lost through transpiration.

[4] Amazon forests lose to evapotranspiration (evaporation plus transpiration) about 12cm of water per month during the dry season.

The *El Niño* episode of 1997-1998 may have pushed about one-third of Amazon forests close to this threshold of death-inducing drought[5] (Nepstad *et al*. 2004, Figure 2), although few measurements are available from the field to know exactly how extensive the damage was. In the central Amazon, tree mortality increased 50 per cent following this drought (Williamson *et al*. 2000). During this same El Niño episode, tropical rainforests around the world suffered high levels of tree mortality (Nakagawa *et al*. 2000, van Nieuwstadt and Shiel 2005)

The drought-induced death of an Amazon forest's dominant organism – its canopy trees – may increase fire susceptibility for years afterwards (Ray *et al*. 2005, Brando *et al*., in press). This is true because the evergreen leaf crowns of Amazon canopy trees, which protect the forest from the intense, equatorial sun like a giant beach umbrella, take many years to replace. The leaf canopy of a mature Amazon forest, which vaults to 45m or more above the ground, separates the intense heat of the leaf canopy, where most of the sun's energy that falls on the forest is intercepted, from the dark, humid forest floor far below. Each canopy tree that dies creates a canopy "gap" through which sunlight penetrates into the forest, warming the forest interior. The heating and drying of the forest floor is the major determinant of forest flammability, and is far greater when the leaf canopy is sparse or close to the ground (Ray *et al*. 2005).

Although ignition from lightning is rare in the central forests of the Amazon, man-made sources of ignition are increasingly abundant. Fires set to burn felled forests in preparation for crops or pasture, or to improve pasture forage, frequently escape beyond their intended boundaries into neighbouring forests. During the severe drought of 1998, approximately 39,000 km^2 of standing forest caught fire in the Brazilian Amazon (Alencar *et al*. 2006), which is twice the area of forest that was clear-cut that year. During the severe drought of 2005 (Aragão *et al*. 2007), at least 3,000km^2 of standing forest burned in the Madre de Dios, Pando and Acre regions of the southwest Amazon (Brown *et al*. 2006). These low, slow-moving fires are deceptively destructive, killing from 7-50 per cent of adult trees (>10cm diameter) (Alencar *et al*. 2006, Balch *et al*. submitted, Barlow and Peres 2004, Cochrane and Schulze 1999). Forest fire can therefore increase susceptibility to fur-

[5] El Niño episodes are associated with severe droughts in the Amazon, Kalimantan, and many other places around the tropics, but are associated with higher rainfall in some other regions.

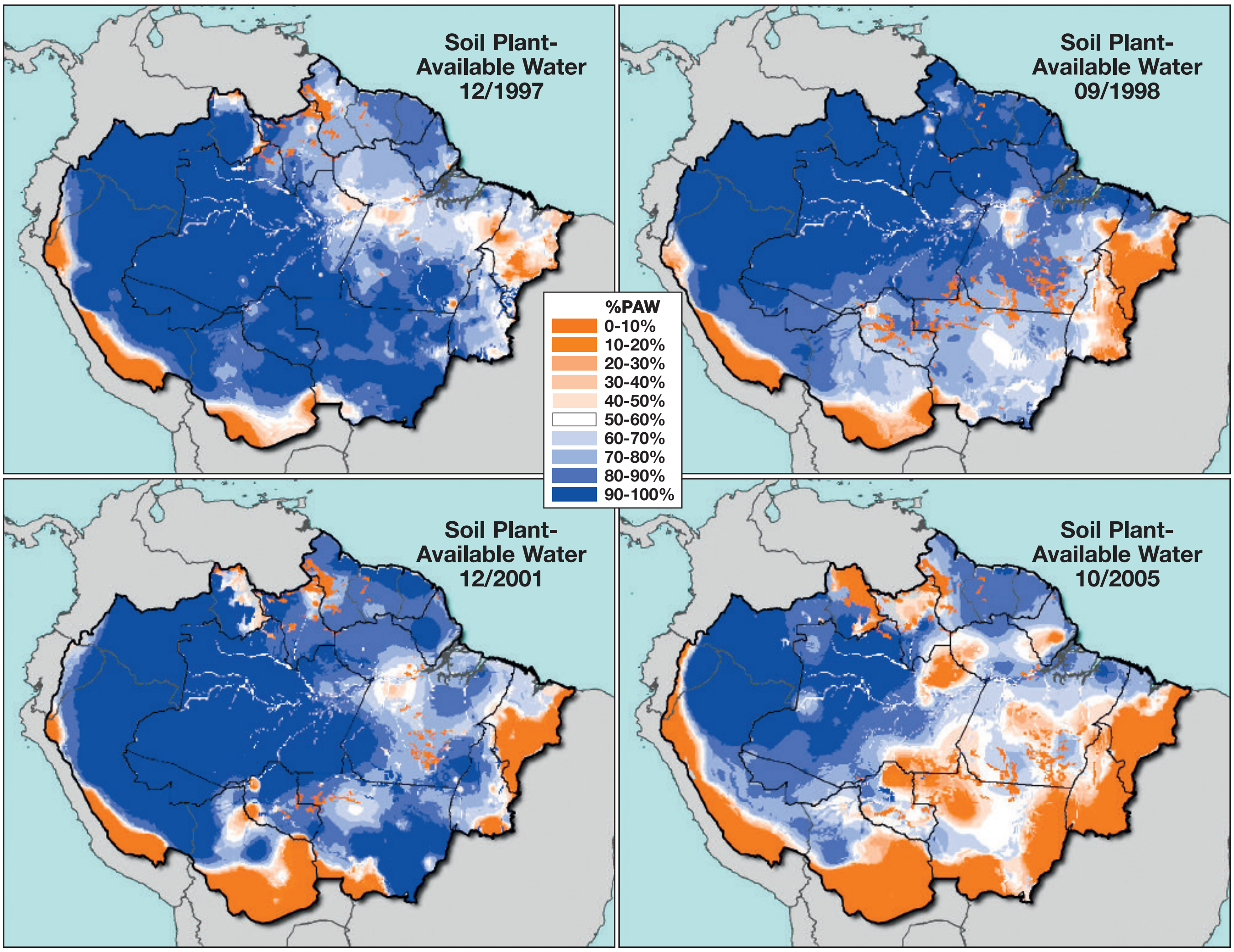


Figure 2. Map of soil moisture levels across the Amazon during four dates of severe drought. This map is an estimation of the percentage of maximum, plant-available soil water (PAW) to 10m depth based on cumulative monthly rainfall and evapotranspiration, updated from Nepstad et al. 2004. Field studies indicate that drought-induced tree mortality begins when PAW declines to 30 per cent of its maximum value (Nepstad et al. 2007), mapped here as tan to brown. Soil moisture depletion is overestimated along the Andes because of data shortages and interpolation errors.

ther burning in a vicious feedback loop by killing trees, opening the canopy and increasing the penetration of sunlight to the forest floor (Nepstad *et al*. 1995, 1999, 2001, Cochrane *et al*. 1999). Selective logging, which can damage up to 50 per cent of the leaf canopy (Uhl and Vieira 1989) is the third major disturbance type that increases forest susceptibility to fire (Uhl and Kauffman 1990, Holdsworth and Uhl 1997, Ray *et al*. 2005).

Forests pushed beyond the tipping point through tree mortality induced by drought, fire, and/or selective logging are vulnerable to transformation into flammable "thickets" or "brush" (Figure 1). Field observations in northeastern Mato Grosso, southeastern and eastern Pará states and near Santarém have found that this fire-prone vegetation is dominated by invasive, sprouting tree species (such as *Solanum crinitum* and *Vismia guianensis*), and, sometimes, grasses (including *Imperata brasiliensis, Paspalum spp.*), bamboo (*Guandu spp.*), and fern (such as *Pteridium aquilinum*) (Nepstad D, unpublished data). Although still rare in occurrence, forests invaded by grasses may be the most susceptible to degradation because of the large amount of fuel produced by many grasses and because of their inhibitory effect on tree regeneration (Nepstad *et al*. 1996). In Southeast Asia, a single grass species (*Imperata cylindrica*) now dominates roughly 300,000km^2 of land that once supported closed canopy forest (McDonald 2004).

There are important gaps in our understanding of the forest degradation process in the Amazon. Forests growing on nutrient-poor soils, such as those growing on white sand, often develop thick root mats above the mineral soil (Kauffman *et al*. 1988), and may be particularly vulnerable to fire-induced tree mortality since a substantial portion of the root system can be killed by fire.
The ecological tipping point of Amazon forests varies

from place to place, but a few general patterns are beginning to appear. Forests are most likely to become degraded when (a) high levels of tree mortality are induced by drought, fire, or logging, (b) seeds, or spores, of high-fuel grasses, ferns, or bamboo are abundant following tree mortality, (c) ignition sources are present, and (d) the forest is subjected to severe seasonal or episodic drought. The portion of the Amazon that is exposed to severe drought episodes is large (Figure 2) and may expand in the future because of human-induced climate change and unabated deforestation and land-use change.

Deforestation, smoke, global warming, and the climatic tipping point

For more than two decades, several teams of scientists have been using computer models to predict the future relationship between the Amazon and climate. How will the Amazon climate change as heat-trapping gases accumulate in the atmosphere, as forests are replaced by cattle pasture, or as *El Niño* episodes become more frequent? None of these modeling efforts are perfect, but they provide a few consistent messages. It appears that the Amazon is heading towards a drier, warmer future, with the greatest rainfall reductions predicted during the dry season and during *El Niño* episodes, when vegetation is most sensitive to rainfall reductions. Deforestation also inhibits rainfall and increases temperatures, while dense smoke can extend the dry season for several weeks. In other words, future trends in the Amazon climate may very well exacerbate the forest degradation that is already underway.

The growing concentration of carbon dioxide, methane, and other heat-trapping gases in the atmosphere has been the topic of several computer modeling"experiments" conducted using global circulation models (GCMs). These models can simulate future climate around the world and its response to the growing radiative forcing of the atmosphere that is associated with the accumulation of heat-trapping gases. More than 60 per cent of the 23 GCMs that were run under scenarios of heat-trapping gas accumulation predict a substantial decline (>20 per cent) in rainfall in eastern Amazonia by the end of the century (IPCC 2007, Malhi *et al*. in press, Figure 3). These models predict an increase in rainfall in the western Amazon, where rains associated with uplifting forced by the Andes may increase because of the greater humidity of the air that is associated with warming. Global warming alone will likely reduce rainfall in the eastern Amazon.

In recognition of the important role that vegetation plays in the climate, some modeling teams have coupled "dynamic vegetation models" to their GCMs in an effort to simulate how climate change will affect the location of different vegetation types and how these changes in vegetation will, in turn, influence climate. One of the most dramatic results came from the United Kingdom's Hadley Center, predicting a large-scale, stable substitution of Amazon rainforest with savanna-like and semi-arid vegetation by the end of the century and an 8°C rise in average temperate (Cox *et al*. 2000, 2004). Other modeling groups have found similar evidence of a new vegetation-climate stable state in the Amazon with much of the eastern portion of the forest replaced by drought-resistant vegetation (Salazar *et al*. 2007, Oyama and Nobre 2003, Botta and Foley 2002). Several coupled climate-vegetation models, however, do not predict this large-scale dieback of the Amazon forest (Friedlingstein *et al*. 2006, Gullison *et al*. 2007). Global warming may lead to the displacement of large areas of eastern and central Amazon forest, reinforcing a drying trend.

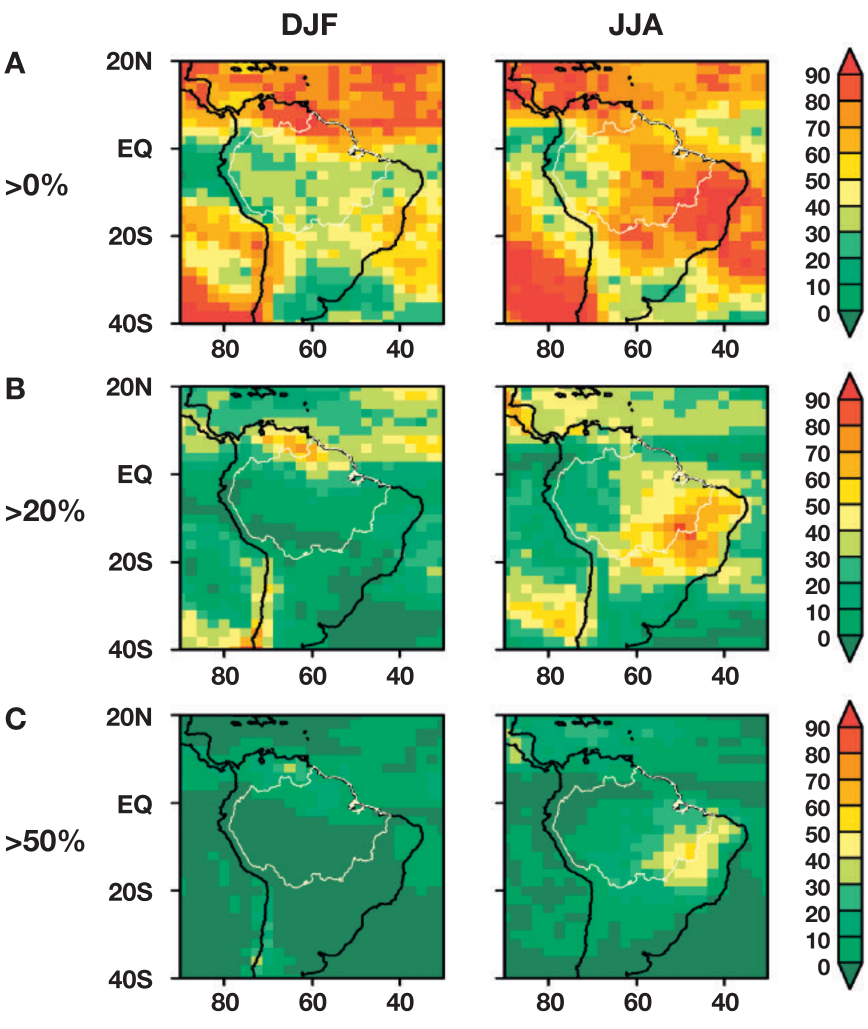
Several climate modeling experiments involving the complete replacement of Amazon forest by cattle pasture indicate large reductions in rainfall and higher temperatures (Nobre *et al*. 1991, Shukla and Nobre 1990, Lean and Warrilow 1989). Two climate modeling teams (Sampaio *et al*. 2007, da Silva *et al*. 2007) have now simulated future Amazon climate using modeled projections of future deforestation (Soares *et al*. 2006). Da Silva *et al*. (2007), using a high-resolution modeling system, found that forest clearing may exacerbate the Amazon drying trend that is a likely outcome of global warming, especially during *El Niño* episodes, although the absolute rainfall reduction is somewhat less than that predicted by GCMs. Sampaio *et al*. (2007) also found evidence of increasing rainfall inhibition by an expanding deforestation frontier. If soybeans are the drivers of deforestation instead of the cattle pasture, rainfall reductions may be much higher (Sampaio *et al*. 2007, Costa *et al*. 2007). Deforestation alone inhibits rainfall, particularly when it affects 30 per cent or more of forest cover.

The GCM models also predict that global warming will bring higher air temperatures to the Amazon region, with most projections hovering around 2°C increase in average air temperatures, but with some predictions as high as 8°C (IPCC 2007). Higher temperatures will evaporate water more rapidly, exacerbating the drying trend associated with lower rainfall. The distribution of rainfall through time is also likely to change in the Amazon as global warming intensifies. The greatest decline in rainfall will probably be in the dry season (Fig. 3), when the largest share of rain comes from moist air rising off the land. Vegetation is most sensitive to water deficits in the dry season. With more energy and moisture in the atmosphere, extreme weather events will probably become more common, with a greater frequency of torrential rain events and high winds (IPCC 2007), leading to increased disturbances in the Amazon.

The coupled climate-vegetation models are blunt instruments in the quest to understand the Amazon's fate in a rapidly changing world that provide an important glimpse into the climate at the end of the century. It is important to examine the changes in Amazon climate that are already underway and that may shape the forests of the region over the next 10-30 years. Episodic droughts that are already occurring in the Amazon may be sufficient to foster large-scale brushification of the region's forests.

Current oscillations in Amazon climate are often associated with changes in sea surface temperature. The temperature of the ocean surface influences where on the planet warm moist air will rise, producing rainfall, and where dry, cooler air will sink, inhibiting rainfall. Rainfall tends to decline in the eastern Amazon when sea surface temperatures rise along the Pacific coast of northern South America during *El Niño* episodes (Marengo *et al.* in press). The warming of the sea surface between western Africa and the Gulf of Mexico – called the Northern Tropical Atlantic Anomaly (NTAA) – is also associated with drought in the Amazon Basin, but with the greatest influence being in the western Amazon (Marengo *et al.* in press). Some climatologists believe that these sea surface temperature anomalies will become more frequent as greenhouse gases accumulate further in the atmosphere (Timmerman *et al.* 1999, Hansen *et al.* 2006, Trenbarth and Hoar 1997).

Regional climate analyses and modeling have also found evidence of more localized changes in rainfall associated with the clearing of forest land, including evidence that there is an initial increase in rainfall when forest clearings are a small portion of the forested landscape that is followed by a decrease in rainfall as clearings grow in size (Silva Dias *et al.* 2002, da Silva and Avissar 2007).



One of the most important discoveries in helping us understand the potential of reaching a climatic tipping point is rainfall inhibition by clouds (Andreae *et al.* 2004). When aerosol particles from biomass fires become very dense in the atmosphere, there is an excess of condensation nuclei, and individual

Figure 3. Most climate models predict substantial drying (>20 per cent) of the eastern Amazon by the end of the century. These maps summarize the results of 23 global circulation models run for the Intergovernmental Panel on Climate Change's moderate scenario of greenhouse gas accumulation for the end of the century. The bar on the right provides the color scheme for the percentage of these models that predict increased drought in the Amazon by the end of the century, including any increase in drought (A), at least a 20 per cent increase in drought (B), and at least a 50 per cent increase in drought (C). Predictions are for the dry season in the northern Amazon (December, January, February, on the left) and in the southern Amazon (June, July, August, on the right). (Malhi et al. in press)

water droplets do not become heavy enough to fall to the ground as rain. The scientific community still does not know how important this phenomenon is for influencing the total amount of rainfall, but there is anecdotal evidence that this rainfall inhibition is already exerting an effect on farmers and ranchers. Pilots and farmers in the Xingu headwaters region of Mato Grosso claim that the rainy season begins later in the year when the density of smoke is high (J. Carter, pers com.). Dense smoke can inhibit the initiation of the rainy season for several weeks.

New pressures to deforest may accelerate the die-back

Several trends in agriculture, livestock, and commodity markets may speed the rate of forest clearance in the Amazon and with it the likelihood of a near-term forest dieback. First, large areas of southern and eastern Amazonia have eradicated foot-and-mouth disease, opening much of the region's cattle industry to export from the Amazon, often for higher prices (Kaimowitz *et al*. 2004, Nepstad *et al*. 2006a, Arima *et al*. 2006). Latin America is striving to completely eradicate foot-and-mouth disease in the region (PAHO 2004), which would further strengthen ranching. Second, the rising international demand for agro-industrial commodities, such as soybean, is colliding with the scarcity of appropriate land for agro-industrial expansion in the United States of America, western Europe, China, and many other agricultural countries (Nepstad and Stickler in press). As a result, much of the recent global surge in the expansion of cropland area is taking place in the Brazilian Cerrado and Amazon regions, where more than 1,000,000km^2 of land suitable for agro-industrial expansion is still available for the expansion of mechanized production (Shean 2004, Nepstad *et al*. 2006a, Figure 4). Third, the rising price of oil has triggered new national policy initiatives in the United States of America, the European Union, and Brazil that feature the expansion of biofuel as a substitute for gasoline and diesel (Yacobucci and Schnepf 2007). Brazilian sugar cane ethanol will supply much of the growing global demand for ethanol because it is one of the world's most efficient and inexpensive forms of ethanol (Pimentel and Patzek 2005, World Watch 2006, Xavier 2007), and it has the greatest potential for expanded production. Although most of the expansion of sugar cane production will be in southern and central Brazil, it will influence the Amazon indirectly by displacing soybean production and cattle ranching. Finally, crop breeding programmes primarily in Brazil (Cattaneo in press) have produced varieties of soy and other crops that are tolerant of the high temperatures and humidity of the Amazon region. The combination of these and other factors signifies growing economic pressures to convert Amazon forests to cattle pastures and cropland, and an expanding source of ignition and invasive plants for flammable forests across the region. It also signifies that deforestation-driven inhibition of rainfall through smoke and through changes in land cover could take place more rapidly than current trends.

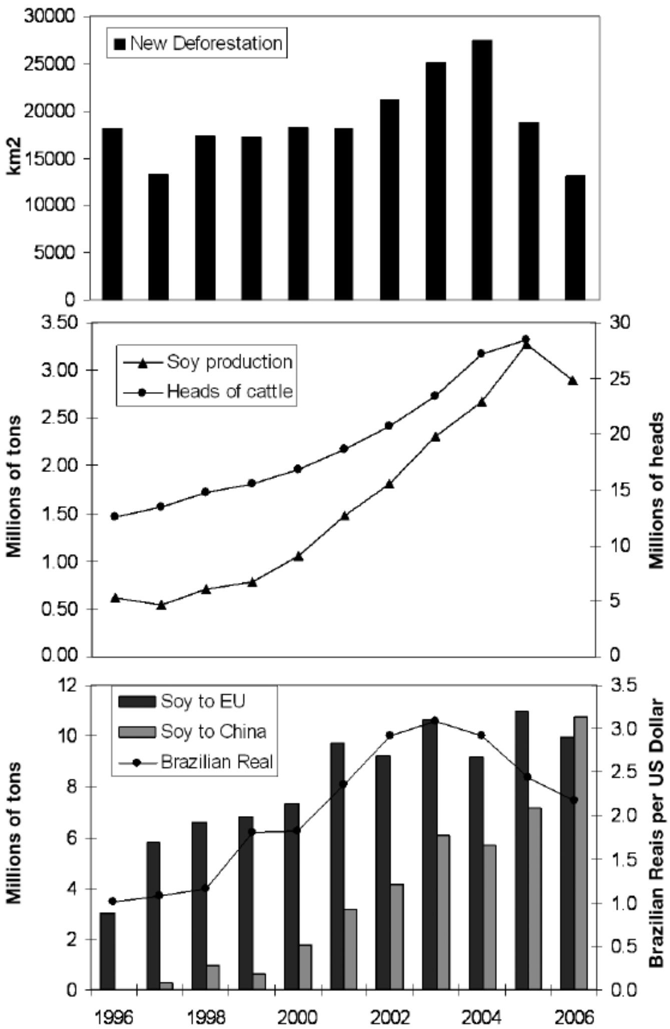


Figure 4. Recent trends in deforestation in the Brazilian Amazon, the expansion of the Amazon cattle herd, Amazon soy production, the value of the Brazilian currency (Real) against the US dollar, and Brazilian soy exports to the European Union and China. Expanding international demand for soybean and other agricultural commodities is pushing new cropland into the Amazon, displacing cattle ranching towards the core of the region. New demands for biofuels may exacerbate this trend. The recent decline in deforestation was associated with declining prices for soybeans, cattle, and a strengthening of the Brazilian Real, but may have also been caused by the new protected areas created through the ARPA programme and greater government investment in enforcement of land legislation (Updated from Nepstad et al. 2006). Initial estimates of 2007 deforestation indicate higher deforestation, perhaps a reflection of higher soy and beef prices.

Another important change underway in the Amazon that will also favour acceleration of forest clearing, including deep into the core of the region, is the paving and construction of all-weather highways into regions that were previously "passively" protected by their remoteness (Nepstad *et al*. 2000, 2001, 2002, Alves *et al*. 2003, Figure 5). The investments in highways lower the cost of transporting inputs to the agricultural frontier and products to markets, and therefore increases the profitability of market-oriented farming and livestock production. *Hidrovias* (waterways) are also under discussion, particularly along the Madeira River where two new hydroelectric reservoirs would be used to facilitate barge transport into Bolivia as well as generate energy. With the paving of the inter-oceanic highway from Assis, Brasil, to Cuzco, the imminent paving of the BR319 highway from Manaus to Porto Velho, and the BR163 highway from Santarem to Cuiabá, the cost of transport will decline drastically across large regions of the Amazon, increasing the likelihood of an economic tipping point.

Racing towards a dieback?

Several forces are pushing the Amazon forest towards a near-term dieback. Logging crews extend their road networks deeper into the core region of the Amazon forest, extracting only a portion of the forest's wood, but thinning the canopy greatly through collateral damage to the trees that remain in the forest. The loggers are followed by cattle ranchers who send their chainsaw crews to fell the forest in preparation for pasture formation, capitalized through the sale of their land to soy farmers. And with the seeds of their African forage grasses come the hitchhiking seeds of pernicious weeds that spread across the landscape, sometimes invading forests damaged by logging and fire. Periodic severe droughts associated with El Niño episodes and the Northern Tropical Atlantic Anomaly (NTAA) parch large fractions of the region's forests, increasing their susceptibility to the fires that escape from the farmers fields and the ranchers pastures, and further damaging the forest through tree mortality. Dense palls of smoke can extend the dry season for additional weeks, increasing the area of forest that is burned by escaped fires, as explained above.

How much time remains to prevent a large-scale forest dieback in the Amazon? How long will it take for the synergistic processes of forest degradation, rainfall inhibition, and deforestation to claim half the forest?

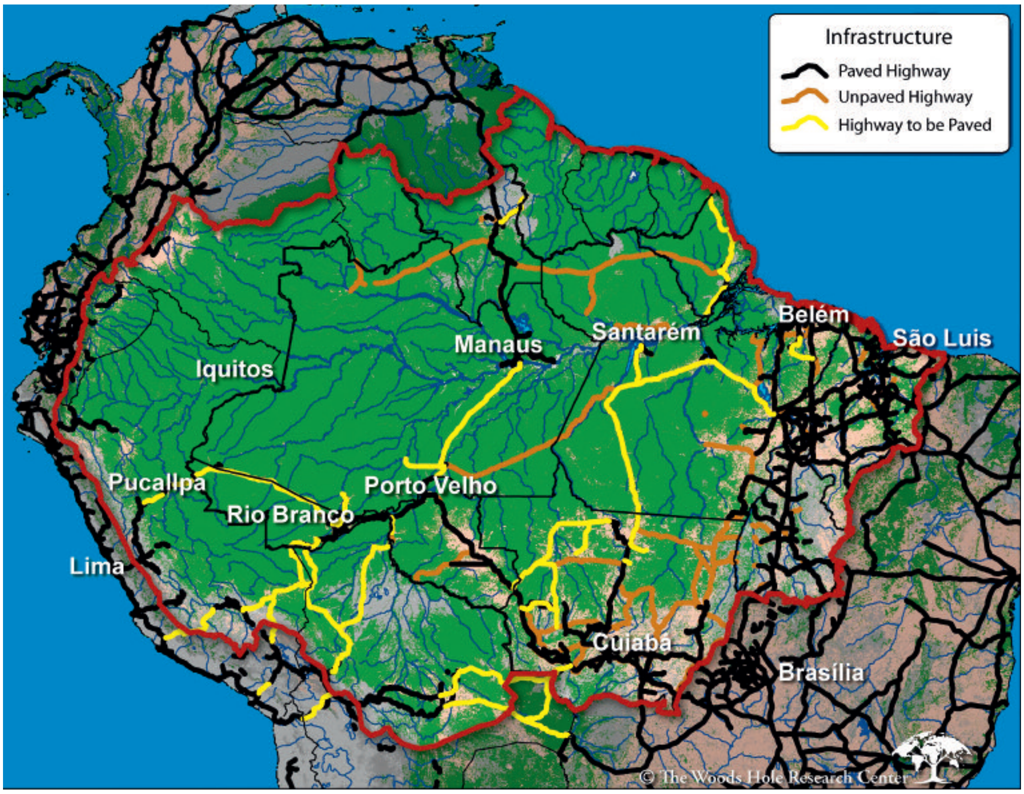
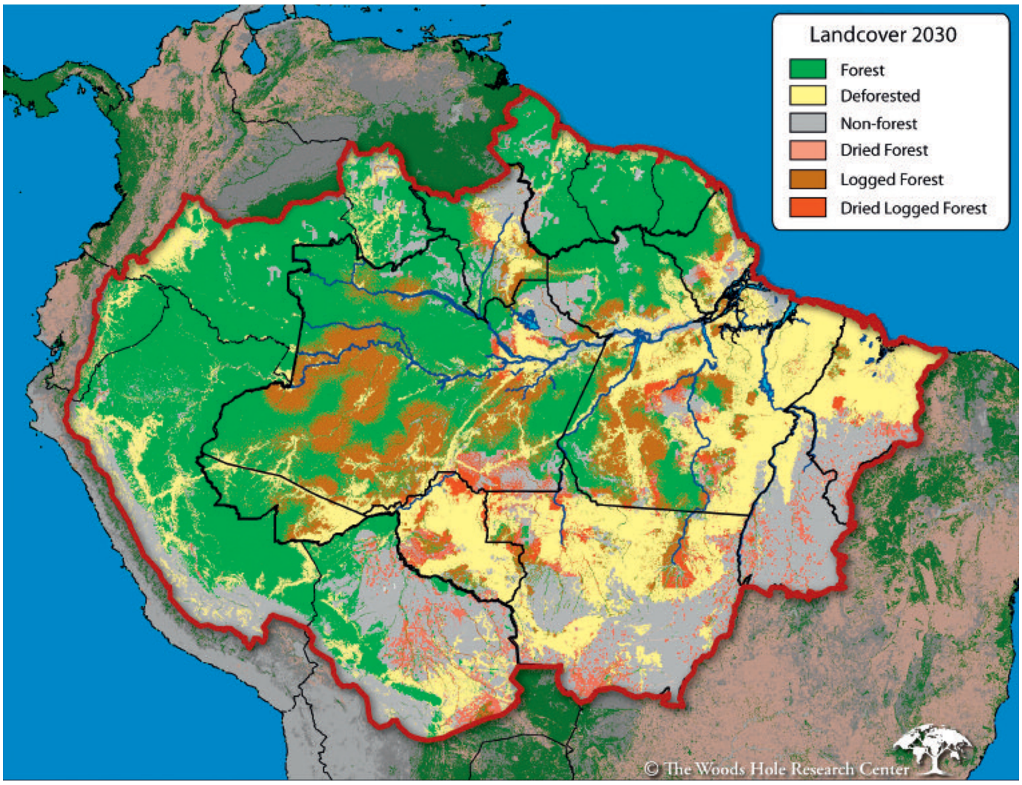


Figure 5. Amazon highways. The core region of the Amazon will soon be accessible by all-weather highways (yellow) as paving plans unfold. These investments in transportation lower the production costs of ranching and farming, potentially stimulating deforestation.

Figure 6. A forest racing towards an ecological and climatic tipping point? Map of Amazonia 2030, showing drought-damaged, logged, and cleared forests. This map assumes that deforestation rates of 1997-2003 continue into the future, and that the climatic conditions of the last 10 years are repeated into the future. See text for further detail.



This report presents a preliminary assessment of the potential for a near-term forest dieback and its ecological consequences (Figure 6)[6]. This assessment is conservative because it assumes that deforestation rates will follow those observed in the 1998-2003 period (Soares *et al*. 2006), it assumes that the climate of the last 10 years repeats itself into the future, it does not include smoke-inhibition of rainfall, nor does it consider deforestation-induced inhibition of rainfall. We do not invoke fire in this estimate, although it is likely that a substantial portion of the forests that are damaged by drought and/or logging, and additional forests that are not damaged, will experience understory fire. Under these assumptions, 31 per cent of the Amazon closed-canopy forest formation will be deforested (up from 17 per cent currently) and 24 per cent[7] will be damaged by drought or logging by the year 2030. If we assume that rainfall declines 10 per cent in the future, then an additional 4 per cent of the forests will be damaged by drought.

If we assume that carbon release from deforestation is as described in Soares *et al*. (2006), that selective logging releases 15 per cent of forest carbon stocks to the atmosphere (Asner *et al*. 2005), that drought damage causes a 10 per cent reduction in forest biomass (Nepstad *et al*. 2007), and that fire affects 20 per cent of the forests damaged by drought or logging releasing an additional 20 per cent of forest carbon to the atmosphere, then 15-26 of the 90-140 billion tonnes of carbon contained in Amazon forest trees will be released to the atmosphere through the early stages of an Amazon forest dieback. In other words, the changes that are taking place in the Amazon today could undo many of the advances in the reduction of greenhouse gas emissions that have been negotiated within the Kyoto Protocol, which, if fully implemented, will achieve a 2 billion tonnes reduction of carbon emissions during the period 2008-2012.

This near-term forest dieback will come at great costs to Amazon society. Fire alone will lead to the deaths of hundreds of Amazonians and the illness of tens of thousands through bronchial ailments. Travel and electrical transmission will be interrupted, and many rural investments in cattle pasture fencing, orchards, and forest timber management will be lost.

[6] We assume "business-as-usual" patterns of deforestation as estimated by Soares et al. (2006), Amazon climatic conditions of the January 1996 through December 2005 decade (updated from Nepstad et al. 2004) are repeated into the future, that a tree mortality threshold is exceeded when plant-available soil water (PAW) falls below 30 per cent of its maximum value to a depth of 10m (using the map of maximum PAW presented in Nepstad et al. 2004, and the mortality threshold of Nepstad et al. 2007), and that logging will expand across the Amazon as described in the rent-based economic model of Merry et al. (in review).

[7] There have been no basin-wide estimates of the total area of forest damaged through logging, fire, and drought.

The costs of fire in the Brazilian Amazon can be very high. In 1998, the health, agricultural, forestry and carbon impacts of fire may have been as high as $5 billion (Mendonça *et al*. 2003). More frequent and intense droughts will lead to fish kills and low river levels, cutting riverine communities off from nearby markets, and health and education services (Marengo *et al*. in press).

Many of the losses associated with a forest dieback are more difficult to quantify monetarily. By the year 2050, four ecoregions will be reduced to less than 15 per cent of their current ranges, including the Maranhão babaçu forest, the Marañon dry forest, and the Tumbes/Piura dry forest (Soares *et al*. 2006). The cloud forests of Bolivia and Peru may disappear if changing regional climate inhibits the rain and high elevation clouds that are the necessary conditions for this ecosystem to exist, a process that has already led to the extinction of golden toads in the central American cordillera (Lawton *et al*. 2001). Global warming alone may move the climate belts of the eastern Andean slope upward faster than the plant species can migrate (Bush *et al*. 2004). And many animal species will be squeezed through habitat destruction. Only a tenth of the habitat of the marmoset *Mico argentatus* will remain forested and a fourth of all mammals will lose at least 40 per cent of their territories to forest clearing by the year 2050 (Soares *et al*. 2007).

And, yet, this scenario may be conservative. If increases in deforestation were to occur because of the rising price of biofuel and agricultural commodities, or rainfall is substantially inhibited by deforestation or smoke, the speed of the dieback could easily double. Small increases in drought or deforestation might accelerate forest destruction and degradation so that it surpasses the 50 per cent marker within the next 15 years.

Avoiding an Amazon tipping point: key processes

Several important processes and relationships hold the potential to counteract the forces that are driving the Amazon towards a dieback scenario and provide some of the elements of a bold Amazon conservation strategy.

• ***In the absence of fire, most forests recover rapidly.***
Most of the degraded lands of the Amazon will return to closed-canopy forest if protected from fire, recovering the transpiration of primary forests within 15 years' time (Uhl *et al*. 1988, Nepstad *et al*. 1991, Jipp *et al*. 1998). Forest regrowth proceeds at a rate that is determined largely by the intensity of use prior to abandonment (Uhl *et al*. 1988, Zarin *et al*. 2001, Davidson *et al*. 2007). Abandoned cattle pastures established on soil that was never ploughed are generally quickly grown over by resprouting trees and lianas which develop into closed-canopy secondary forests within 5-10 years. With each year of fire-free recovery, the average height of the regrowing forest canopy is higher, its flammability declines, (Ray *et al*. 2005; Holdsworth and Uhl 1997) and the amount of rain-cloud-forming vapour that is pumped into the atmosphere increases (Jipp *et al*. 1998).

• ***As fire-averse landholders become more numerous, fire-dependent landholders may follow suit.***
Landholders avoid the use of fire as a land management tool and invest more in the prevention of accidental fire as they accumulate fire-sensitive investments such as orchards, tree crops, forest timber management systems, and improved forage on their properties (Nepstad *et al*. 2001, Bowman *et al*. submitted). As the number of fire-averse landholders in a landscape increases, a turning point may be reached beyond which these landholders prevail upon their fire-using neighbours to reduce fire risk. Such a shift in landholder behaviour – if it in fact occurs – could play a strong role in preventing fire-induced forest degradation from taking place.

• ***The growing demand for higher environmental performance that is evident among the buyers and financiers of agricultural commodities could move the Amazon agro-industrial and livestock sectors towards greater compliance with the law and the adoption of best agricultural practices.***
A second change in landholder behaviour could occur when sound land stewardship, including the judicious use of fire, and compliance with environmental legisla-

tion are viewed by a growing number of producers as the necessary conditions for participating in commodity markets and for obtaining access to credit and financing. The soy growers of Mato Grosso are in the midst of such a change today as they enter their second year of a moratorium imposed by the Associação Brasileiro de Indústrias de Óleos Vegetais (The Brazilian Vegetable Oil Industry Associaton – ABIOVE). This two-year moratorium on the purchase of soy planted on soils recently cleared from Amazon forest was stimulated by a campaign against Amazon soy initiated by the environmental organization Greenpeace (Greenpeace 2006). Soy producers and their organizations are currently seeking criteria systems that would certify their farms as environmentally sound, and such systems are under development. For example, the Roundtable for Responsible Soy (RTRS), initiated by WWF-World Wide Fund for Nature in 2004, is now engaged in an international, multi-stakeholder process of defining the criteria by which responsible soy producers will be identified and certified. The RTRS includes in its membership purchasers of 20 per cent of the world's annual soy crop, all of whom are committed to purchasing RTRS-certified soy. On a smaller scale, the Registry of Socioenvironmental Responsibility (Cadastro de Compromisso Socioambiental – CCS), launched by two non-governmental organizations (Aliança da Terra – AT and Instituto de Pesquisa Ambiental da Amazonia – IPAM) has attracted 75 ranchers and farmers whose properties have a combined area of 1.5 million hectares (Arini 2007). Entry into the Registry commits the landholder to implementing sound land stewardship and labour relations on their properties that is made transparent to potential buyers through a website. In 2006 and 2007, two supermarket chains and Brazil's largest chicken producer approached AT and IPAM to purchase soy and beef from CCS properties. It is in the context of certification systems such as these that landholders agree to adopt fire prevention techniques, such as fire breaks along their forest borders, to comply with the private forest reserve requirements of federal legislation, and to conserve their riparian zones.

• Forest recovery and tree crop establishment on degraded lands can restore transpiration and buffer regional climate against extreme climate events.
Water vapour produced by forests in the eastern Amazon is crucial to the maintenance of rainfall systems downwind, in central and western Amazonia (Marengo *et al*. in press, da Silva *et al*. in press). One way to buffer the Amazon against extreme climatic events is to re-establish forest transpiration on the vast landscapes that have been cleared along the Belém-Brasília highway in eastern Pará and Maranhão, and along the PA150 highway in central Pará. The recovery of transpiration over large landscapes through forest regrowth and through the establishment of tree crops together with the reduction of fires could reduce rainfall inhibition provoked by the replacement of native forest with cattle pastures and soy fields. As forest recovery increases rainfall, a virtuous feedback loop of more rapid forest recovery could be established.

• Sustainable timber management
It is possible to profitably manage Amazon forests for sustained timber production while greatly reducing the negative impact of logging on the forest (Holmes *et al*. 2002, Barreto *et al*. 1998). "Reduced impact" logging techniques, including pre-harvest cutting of lianas, careful mapping of skidder trails, directional felling of trees, and other practices, provides equal profits to logging companies (Holmes *et al*. 2002, Barreto *et al*. 1998) as it greatly reduces the damages to the forest canopy that increase forest susceptibility to fire (Holdsworth and Uhl 1997). Amazon conservation will depend upon harnessing the economic value of the region's timber to foster a transition to a forest-based, fire-averse economy (Nepstad *et al*. 2006d).

• Regional planning to reduce the negative impacts of transportation infrastructure projects
From January 2004 through 2006, 23 million hectares of land in the Brazilian Amazon were declared forest reserves (Campos and Nepstad 2006). This historical achievement in tropical forest conservation will avoid approximately 1 billion tonnes of carbon to the atmosphere through the year 2015 by increasing the scarcity of forest available to cattle ranching and soy interests (Nepstad et al. 2006c, Soares et al.2006). This achievement was possible in part because of Brazil's Amazon Region Protected Area (ARPA) programme, which, in cooperation with the World Bank, Global Environment Facility, German Government, and WWF, established a goal of expanding the protected area network to 12 per cent of the Brazilian Amazon land area. But it was also possible because of an extensive process of regional planning involving hundreds of organizations of farmers, logging companies, environmental groups, and government. This regional planning process was initiated in anticipation of the paving of the BR-163 Santarém-Cuiabá highway, and as part of the regional development programme of the Transamazon Highway social movement. It created a broad base of political support for the creation of new protected areas in an active agricultural frontier (Campos and Nepstad 2006).

• REDD: a powerful new mechanism for compensating tropical countries that protect their forests?

Is the world ready to pay for tropical countries to lower their emissions of heat-trapping gases from deforestation and forest degradation? There are reasons to believe that a new regime of international climate policy is imminent in the next few years. Within the UNFCCC, negotiations to create a mechanism for nation-wide compensation of tropical countries that succeed in reducing their emissions from deforestation and forest degradation (REDD) are advancing rapidly. Within Brazil, a pact for the gradual reduction of deforestation to zero has garnered broad support within the national congress, among state governments, and the environmental community. The Aliança de Povos da Floresta (Alliance of Forest People) has presented its support for REDD with a series of conditions involving the compensation of forest people in their role as forest guardians – forests located in indigenous reserves are protected just as much as forests located in parks and biological reserves, based upon satellite analyses of deforestation (Nepstad *et al*. 2006a). A robust mechanism for providing economic incentives for tropical forest conservation could go a long way in preventing the Amazon from reaching its climatic and ecological tipping points.

Conclusion

Synergistic trends in Amazon economies, vegetation, and climate could lead to the replacement or damaging of more than half of the closed-canopy forests of the Amazon Basin over the next 15 to 25 years, undoing many of the successes currently in progress to reduce global emissions of greenhouse gases to the atmosphere. Counteracting these trends are emerging changes in landholder behaviour, recent successes in establishing large blocks of protected areas in active agricultural frontiers, important market trends favouring forest stewardship, and a possible new international mechanism for compensating tropical nations for their progress in forest conservation, that could reduce the likelihood of a large-scale dieback of the Amazon forest complex. In the long term, however, the avoidance of this scenario may depend upon worldwide reductions of greenhouse gas emissions that are large enough to prevent global temperatures from rising more than a degree or two.

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