Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin

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The Amazon Basin is one of the world's most important bioregions, harboring a rich array of plant and animal species and offering a wealth of goods and services to society. For years, ecological science has shown how large-scale forest clearings cause declines in biodiversity and the availability of forest products. Yet some important changes in the rainforests, and in the ecosystem services they provide, have been underappreciated until recently. Emerging research indicates that land use in the Amazon goes far beyond clearing large areas of forest; selective logging and other canopy damage is much more pervasive than once believed. Deforestation causes collateral damage to the surrounding forests – through enhanced drying of the forest floor, increased frequency of fires, and lowered productivity. The loss of healthy forests can degrade key ecosystem services, such as carbon storage in biomass and soils, the regulation of water balance and river flow, the modulation of regional climate patterns, and the amelioration of infectious diseases. We review these newly revealed changes in the Amazon rainforests and the ecosystem services that they provide.

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The Amazon Basin is generally regarded as one of the world's most important ecological systems, mainly because it includes the largest remaining area of tropical rainforest (Figure 1). These forests contain one of Earth's greatest collections of biological diversity (Dirzo and Raven 2003), including a rich array of plant, animal, and microbial life-forms, which are vital for the functioning of the biosphere.

In a nutshell:

- While tropical deforestation is a well-known environmental problem, many aspects of this issue have been overlooked until recently
- The degradation of tropical rainforests goes far beyond clearing large areas of trees; selective logging, collateral forest damage, and the replacement of old growth stands are also widespread
- In addition to providing agricultural and timber commodities these landscapes may also sequester carbon, regulate freshwater and river flows, modulate regional patterns of climate, and ameliorate infectious diseases
- The loss and degradation of tropical rainforests and the services they provide may be greater and more widespread than previously reported

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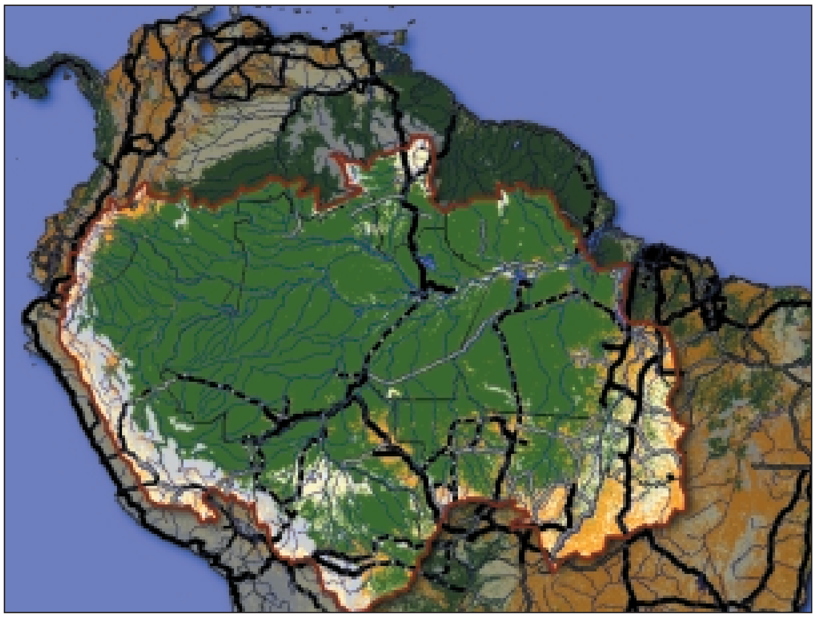
The rainforests of the Amazon also provide crucial ecosystem goods and services to humanity, including many that have considerable economic and societal value (Myers 1997). The term "ecosystem goods and services" has become widely used in recent years, and typically refers to the supply of valuable products and materials (including agricultural, forest, mineral, and pharmaceutical commodities), the support and regulation of environmental conditions (through processes like pollination, flood control, and water purification), and the provision of cultural and aesthetic benefits (including ecotourism, heritage, and sense of place) by ecosystems (Daily 1997; Millenium Ecosystem Assessment 2003; DeFries *et al.* 2004).

Many of the ecosystem goods and services derived from the Amazon Basin (eg from timber, pasture, and soybean production), are easily recognized and are revealed on local scales – often within individual land parcels that are specifically managed for those purposes. Other ecosystem services, such as pollination and flood control, are somewhat less obvious and may appear over larger spatial scales, extending over complex landscapes and whole watersheds. Tropical rainforests also provide ecosystem services that are manifested at the scale of the whole Amazon Basin and, indeed, the planet. For example, rainforests in the Amazon sequester carbon from the global atmosphere, regulate the water balance and flow of the entire Amazon River system, influence the patterns of climate and air chemistry over much of the continent, and may even ameliorate the spread



Courtesy of P Lefebvre, Woods Hole Research Center

Figure 1. *The Amazon Basin. Map illustrating the spatial extent of the Amazon drainage basin across South America, superimposed on a vegetation map of the region. Green indicates the current distribution of forest, whereas tan and white indicate areas of deforestation and non-forest, respectively. The geographic location of major roads is also indicated: black lines are paved roads, grey are unpaved roads, and dashed lines indicate roads that are scheduled to be paved.*

of vector-borne and water-borne diseases across the region.

But the long-term sustainability of Amazonian rainforests, and the multiple goods and services they provide, may now be under threat from human actions. The region has been experiencing high rates of deforestation for many years, and this may now be affecting the ecological integrity of the forests. By the year 2000, nearly 15% of the forests in the basin (~400 000–500 000 km^2) had already been cleared (Nepstad *et al.* 1999). Recent rates of deforestation continue to be very high; between 2002 and 2004, the highest rate of forest clearing for any 3-year period to date was recorded (INPE 2004). This trend is likely to continue as more roads are built through the core of the forest, and growing international markets for free-range beef and soybeans drive increasing demand for agricultural products (Carvalho *et al.* 2001; Alencar *et al.* 2004; Soares-Filho *et al.* 2004).

Here we review recent research on changes in the Amazon rainforests and the ecosystem goods and services they provide. Many of these results build upon our previous notions of deforestation and the subsequent loss of biodiversity and ecological functioning. However, some new results have dramatically changed our perceptions of deforestation, the ecological and societal value of the tropical rainforests, and how changes in the forest may affect human relationships with these unique ecosystems.

■ Revisiting deforestation in the Amazon

Many previous studies have used satellite-based "snapshot" images of forest cover to estimate the rates of forest clearance in the Basin (eg Skole and Tucker 1993; Morton *et al.* 2005). These efforts have given us the means to quantitatively describe the amounts and spatial patterns of deforestation. For example, we now know that deforestation is largely focused in the transition areas between forest and cerrado (tropical savanna), along roads, and in the frontier border areas such as Acre and Rondônia (Houghton *et al.* 2000; Cardille and Foley 2003; Soares-Filho *et al.* 2004). Nevertheless, there are still many gaps in our understanding of Amazon deforestation.

Until recently, characterizing deforestation from satellites has focused mainly on estimating the changing areas of "forest" and "non-forest" pixels over time. However, Amazonian landscapes are actually much more dynamic and complex: they experience cycles of clearing, cultivation, grazing, and secondary forest regrowth, resulting in a complex mosaic of intact rainforest, lands under varying management regimes, and recovering secondary forests (Fearnside 1993; Nepstad *et al.* 1999; Cardille and Foley 2003). "Forest" and "non-forest" are not adequate descriptions of the real landscape. Unfortunately, we still do not have a complete understanding of the landscape dynamics of the Basin, that reflects the different rates of gross deforestation (clearing of primary rainforest to establish pastures or croplands), the widely varying management regimes of croplands and pastures, the abandonment of fields leading to regrowth of secondary forests (followed by possible reclearance), and the resulting net changes in forested area (gross clearing minus regrowth; Figure 2). In particular, it is crucial to distinguish regions of regrowing secondary forest, as they provide areas of carbon uptake (Houghton *et al.* 2000), temporary reservoirs of genetic diversity, and some level of soil conservation and flood amelioration.

Selective logging represents an even greater gap in our knowledge. Until recently, clearing forests for croplands and pastures has received the most attention in scientific and political arenas (Houghton *et al.* 2000; Achard *et al.* 2002; Defries *et al.* 2002), but selective logging has now become recognized as another major form of land use in the Amazon. In a ground-breaking estimate of logging activity, based on surveys of mill operators, Nepstad *et al.* (1999) reported that the extent of logging (~9000–15 000 km^2 per year in 1996–97) nearly matched the amount of gross deforestation occurring in the same period. Using a new, high-resolution satellite analysis system, Asner *et al.* (2005) found that selective logging extended over more than 12 000 km^2 each year between 1999 and 2002, with some years seeing rates as high as 20 000 km^2 yr^{-1}. More surprising was the finding that this newly detected logging only overlapped with older deforestation maps – provided by the Brazilian Space Institute (INPE 2004) – by about 6%. Even more unexpected was the finding that only 16% of the logged area turned into deforested (clear-cut) land the following year, and only 32% of the logged forests were consumed by clear-cut deforestation within 4 years (Asner *et al.* 2006). These results completely change our view of logging as a form of land use in the Amazon: first, selective logging often matches, and can even exceed, deforestation each year; second, for the most part, logging does not immediately precede deforestation – it is a distinct form of forest disturbance in and of itself. In short, the footprint of human activity on the Amazon landscape is roughly double that of previous estimates of deforestation alone (Asner *et al.* 2005).

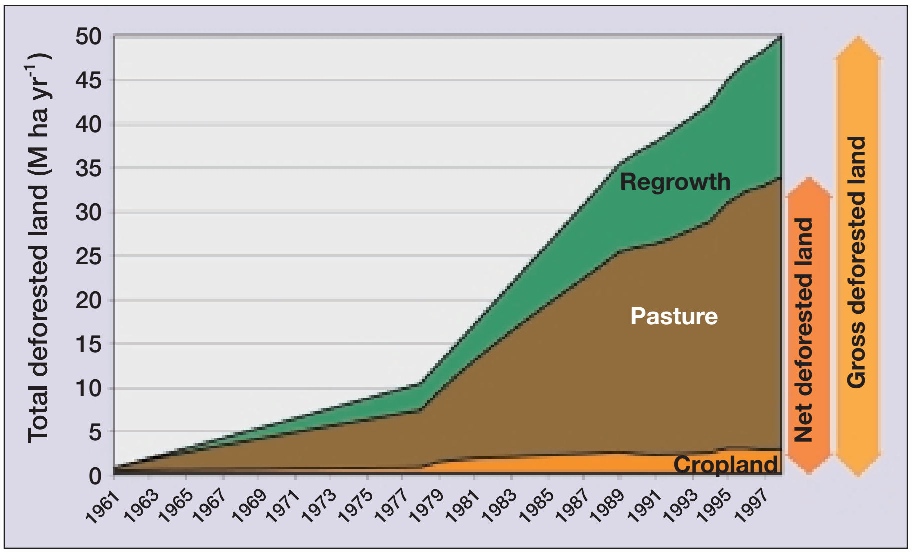


Figure 2. *Gross versus net deforestation. Deforestation in the Amazon is not just the simple removal of trees. A more complete description must consider the different rates of gross deforestation (clearing of rainforest for pastures or croplands), the management regimens of croplands and pastures, the abandonment of fields leading to the regrowth of secondary forests, and the resulting net changes in forested area (gross clearing minus regrowth). Here we have adapted a Markov land-use transition model developed by Fearnside (1993) to estimate that roughly a third of the total deforested land in the Amazon between 1961 and 1997 is currently regrowing (see also Cardille and Foley [2003]). (M = megatons.)*

The ecological impacts of logging are quite different than those of clear-cutting, and vary dramatically across the basin. In some areas, logging is highly selective because international markets accept only a few tree species for use as timber. However, in areas that supply lumber to Brazilian markets, only about 80 species are acceptable (Verissimo *et al.* 1995). Such variations in logging practices lead to concomitant variations in forest damage. Canopy openings in the eastern and central Amazon can encompass 25–50% of the total logged area, and up to 30 trees can be damaged with each tree harvested (Asner *et al.* 2004). The extent and intensity of harvest operations also determines the impact on carbon storage and loss of biomass and soils (Keller *et al.* 2004), the stocks and flows of important plant nutrients, and long-term patterns of forest production (Olander *et al.* 2005).

The effects of deforestation and selective logging may also change the local microclimate and fire regimes, resulting in widespread collateral damage to the forest. For instance, forest clearance and selective logging increase fire occurrence by providing abundant fuel loads and forest edges that are more vulnerable to desiccation during prolonged periods of dry weather (Laurance *et al.* 1998; Cochrane *et al.* 1999; Nepstad *et al.* 1999; Alencar *et al.* 2004; Barlow and Peres 2004). Under natural conditions, fires are a rare occurrence in Amazonian rainforests, so many tree species are highly vulnerable and can be killed by even low-intensity fires. Such changes in the fire regime may have contributed to the catastrophic wildfires that consumed millions of hectares of Amazonian forests in 1997–98 (Laurance *et al.* 1998; Nepstad *et al.* 1999).

These recent studies highlight previously underappreciated manifestations of land use in the Amazon and underscore the realization that the degradation of the Amazon rainforest may be far more pervasive than previously believed. Taken together, this research forces us to adopt a new perspective on the changing nature of these forests, requiring a new look at the ecological implications of human land-use practices in Amazonia.

■ Assessing the ecological impacts of forest decline

Many previous scientific studies of tropical deforestation focused on the negative consequences for biodiversity and ecosystem functioning (eg Turner 1996; Laurance *et al.* 1998). In fact, tropical deforestation has become a *cause célèbre* among many environmental activists and NGOs. However, such land-use practices also offer many benefits. Whether for securing food, freshwater, or raw materials, land use is ultimately central to the sustainability – indeed, the long-term survival – of all human societies (DeFries *et al.* 2004). Even tropical deforestation has positive outcomes: it provides essential resources (eg food, timber, other raw materials) to society, as well as badly needed jobs and income to many developing countries around the world.

Tropical deforestation therefore represents an inherent societal tradeoff (DeFries *et al.* 2004). In general, land-use practices allow some ecosystem goods to be more readily appropriated by human societies, often yielding key economic and social benefits, at least in the short term. However, land use may degrade other ecosystem services

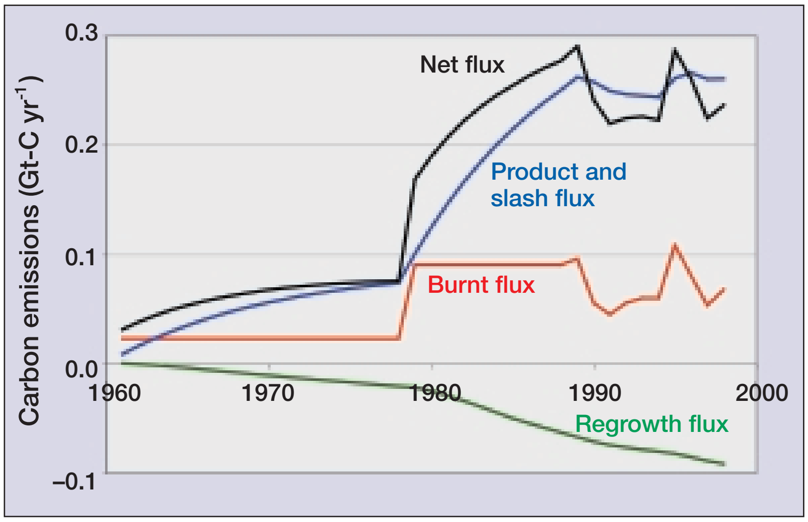


Figure 3. *Estimated carbon emissions from deforestation. We have estimated the carbon fluxes from deforestation over the Amazon Basin from 1961–2000, using a bookkeeping carbon cycle model adapted from Houghton* et al. *(2000). In that paper, it is notable that the largest fluxes of carbon in the 1980s and 1990s resulted from the decay of accumulated slash and product pools, and not from the burnt flux from fires. Moreover, the flux of carbon from accumulating regrowth was of equal magnitude and opposite sign as the burnt flux. (Gt = gigatons.)*

– especially those tied to the long-term functioning of the ecosystem. For example, the loss of rainforests may reduce several critical ecosystem services, such as the supply of non-timber forest products, the availability of pollinating insects, the regulation of climate and carbon stocks, and the regulation and purification of freshwater flows.

In order to make more informed decisions regarding the future of tropical land-use practices, it is necessary to balance the societal benefits (typically the short-term realization of ecosystem goods and commercially valuable commodities) against the long-term costs of ecological degradation (Millennium Ecosystem Assessment 2003; DeFries *et al.* 2004; Foley *et al.* 2005). Such an assessment of tradeoffs must be informed by the best available ecological science, but ultimately these assessments must also be based on societal values (DeFries *et al.* 2004). Recent research has provided new insights into how deforestation and selective logging may negatively affect the flow of many ecosystem goods and services. Here we review four examples.

Carbon storage

The forests of the Amazon play a particularly important role in the Earth's carbon cycle, as they account for nearly 10% of the world's terrestrial productivity and biomass (Melillo *et al.* 1996; Malhi and Grace 2000). As such, the Amazon provides an important ecosystem service to the planet by storing organic carbon in biomass and soil, thereby keeping greenhouse gases (CO_2 and CH_4) from the atmosphere.

The reduction or degradation of forest cover can directly affect carbon storage through losses of vegetation biomass and soil carbon. In most instances, a large and visible portion of the carbon stored in vegetation is released rapidly to the atmosphere through biomass burning. But a smaller, though still substantial, portion of the carbon is returned to the soil as slash (dead plant materials), or is converted to durable products such as paper, lumber, derived wood products, etc. These carbon pools decompose slowly and release CO_2 over a much longer timescale (Figure 3). As a result, some CO_2 emissions from deforestation occur rapidly (from initial clearing and fire), while others occur gradually over many years and decades (from subsequent decomposition of slash and forest products; Houghton *et al.* 2000). In fact, some of today's CO_2 emissions may reflect land-use activities from decades ago.

There are some complicating factors to this picture. First, many estimates of carbon losses from deforestation only account for gross deforestation, while the carbon uptake from recovering secondary forests is sometimes overlooked (Figure 3). Second, deforestation may also indirectly affect carbon storage in nearby forest regions, through changes in local climate and fire regimes (Alencar *et al.* 2004; Barlow and Peres 2004). As noted above, deforestation and selective logging can enhance fuel loads and make forests more vulnerable to desiccation and fire. It is possible that these indirect impacts of deforestation may greatly magnify the loss of carbon storage across the basin (Cochrane *et al.* 1999; Nepstad *et al.* 1999).

Water flow regulation

The Amazon is the largest river system on Earth, providing navigable waters, important food sources, hydroelectricity, and habitat for countless plants and animals (Lundberg *et al.* 2000). The forests of the basin strongly influence this complex hydrological system, largely because they regulate the volume and timing of water and nutrient flows into it. As a result, deforestation has the potential to degrade the regulation of hydrological flows, through changes in evapotranspiration, canopy interception, surface runoff, and groundwater recharge (Meher-Homji 1992; Costa and Foley 1997; Williams and Melack 1997).

There is now compelling evidence to show that changes in forest cover can affect the water balance and hydrology of the Amazon, even if precipitation remains constant. Studies of small watersheds (< 10 km^2) throughout the tropics reveal that runoff and stream discharge generally increase with increasing deforestation (Sahin and Hall 1996). In addition, a recent study by Costa *et al.* (2003) showed that changes in land cover have a substantial effect on large river systems; the authors examined the links between river discharge and vegetation cover in a 176 000 km^2 subcatchment of the Tocantins River basin in eastern Amazonia and found that land-cover changes between the 1960s and 1990s were associated with a ~25% increase in river discharge, even though precipitation in the region did not change (Figure 4).

At larger scales of deforestation, we have only mathematical models to rely upon. Using a detailed biophysical land surface model, Costa and Foley (1997) analyzed the effects of forest removal on the water balance and river discharge of the entire Amazon Basin. Their results showed that deforestation could produce significant increases in runoff and river discharge. Averaged across the entire basin, the model results suggested that widespread deforestation would increase runoff and river discharge by about 20%, although individual watersheds within the basin exhibited increases in discharge ranging from between 5 and 45%, depending on the climate, watershed position, and original vegetation cover.

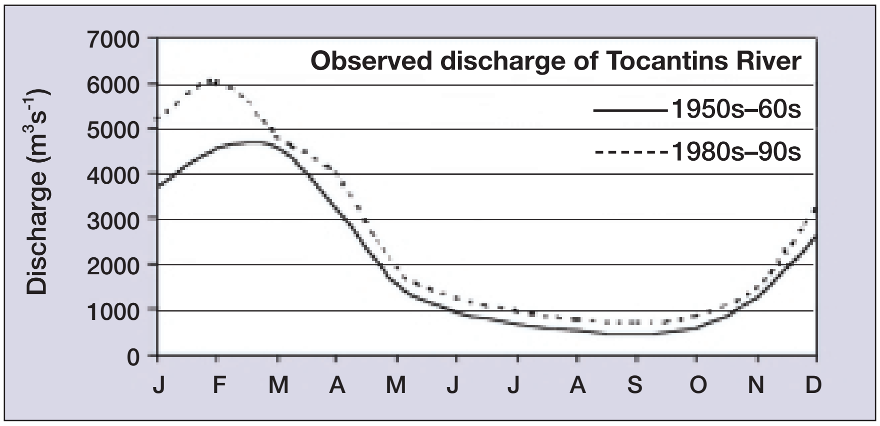


Figure 4. *Effects of land cover change on river flow. Here we illustrate the observed changes in river discharge in the Tocantins river basin that resulted from land-cover change and agricultural clearing in the mid-20th century. The solid line is the mean monthly discharge for the period 1950–60s, when crops and pasture covered about 30% of the land area of the 176 000 km^2 basin. The dotted line is the river discharge during the 1980s and 1990s, when crops and pasture had increased to cover more than 50% of the basin (adapted from Costa* et al. *2003).*

Regional and global climate regulation

The rainforests of the Amazon play a crucial role in regulating the general circulation of the atmosphere. As one of the three major convection centers in the tropics, the Amazon helps to fuel the Hadley and Walker circulations. As deforestation becomes more extensive, the resulting reductions in evapotranspiration and atmospheric heating may weaken moisture recycling and deep convection in the atmosphere over the Amazon, with major repercussions for South American climate (eg Nobre *et al.* 1991; Costa and Foley 2000). Climate model simulations of large-scale deforestation in the Amazon Basin generally show a considerable reduction in evapotranspiration as tropical forest vegetation is replaced with grasses and shrubs; this has the effect of substantially warming the surface and inhibiting convection, regional precipitation, and cloud cover (Figure 5).

The influence of deforestation on climate may also extend far beyond the Amazon Basin. A few recent studies have now illustrated the potential for "teleconnections" from Amazonian climate change, where atmospheric signals may propagate into the middle latitudes, causing changes in the climate of other regions (Snyder *et al.* unpublished; Werth and Avissar 2002). Snyder *et al.* (unpublished) found that deforestation weakens atmospheric convection over the basin and reduces the high-level outflow out of the tropics that interacts with the circulation of the atmosphere in the mid and high latitudes. In their simulations, widespread deforestation causes changes in circulation that alter the North Atlantic and European storm tracks, which could cause substantial cooling in southern Europe and warming across parts of Asia in winter.

Vector-borne diseases

Some of the world's most serious infectious diseases, including malaria, dengue, Leishmaniasis, and several arboviruses, are found in the Amazon basin. Malaria alone kills 1.2 million people worldwide each year, and approximately 40% of the world's population lives in areas where malaria is endemic (WHO 2005). In the Brazilian Amazon alone, there are typically 400 000–600 000 cases contracted annually (WHO 2005).

Rainforests may provide another valuable ecosystem service, moderating the risk of infectious disease by regulating the populations of disease organisms (viruses, bacteria, and other parasites), their animal hosts, or the intermediary disease vectors (most often insects or rodents). For example, the loss of forest cover may affect the abundance and behavior of mosquitoes – a common disease vector in the tropics – through changes in local habitat conditions. Individual mosquito species occupy unique ecological niches and can react rapidly to changes in habitat. For example, in Africa, the larvae of *Anopheles gambiae* are much more likely to survive in deforested landscapes than in intact, forested habitats (Tuno *et al.* 2005).

Previous studies conducted in the Amazon indicated that malaria risk rose sharply during the late 1980s and 1990s (Aramburu Guarda *et al.* 1999). New evidence suggests that changes in forest cover, through effects on the distribution patterns of mosquito vectors, may have contributed to this upsurge in the disease. In particular, a recent project in the Peruvian Amazon examined the links between deforestation and the principle mosquito vector for malaria in South America, *Anopheles darlingi*

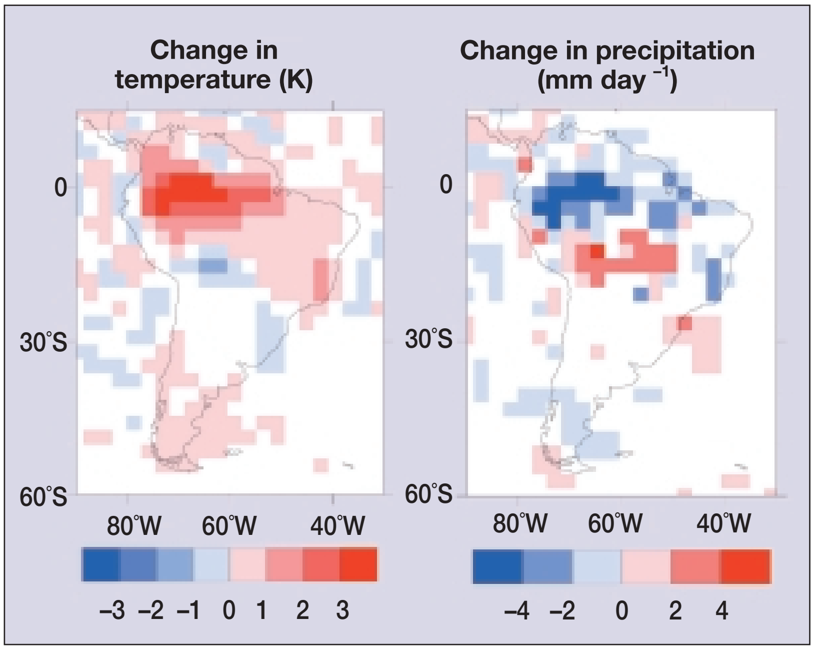


***Figure 5**. Changes in climate over Amazonia from complete deforestation. Snyder* et al. *(unpublished) used the coupled CCM3-IBIS climate–biosphere model to determine the effects of large-scale deforestation on Amazonian climate. The results suggest that the Amazon climate may be highly sensitive to large-scale deforestation (adapted from Snyder* et al. *unpublished).*

(Vittor *et al.* 2006). This analysis suggests a direct relationship between the extent of deforested land and increasing biting rates of *A darlingi*. In fact, heavily deforested areas can see up to a 300-fold increase in the risk of malaria infection, compared to areas of intact forest, controlling for changes in human population density. Furthermore, there appears to be a threshold effect in these data: when the landscape is about 20% deforested, mosquito biting activity increases substantially. In short, deforestation appears to greatly magnify mosquito biting rates and the risk of spreading malaria by increasing habitat available for *A darlingi*.

This work demonstrates that the extent and pattern of deforestation may degrade the disease regulation services of the rainforest. Specifically, links between deforestation, changes in local habitat conditions and biodiversity, and the ecology of *A darlingi* resulted in greatly increased risk of malaria. However, this result could be even more general; deforestation may also amplify other disease risks as well (Patz *et al.* 2005). It is also likely that changes in forest cover (and associated changes in rivers and regional climate) could affect human health through changes in food and freshwater availability, or in water and air quality. Overall, an important conclusion of these studies is that maintaining intact rainforest ecosystems may provide many health-related ecosystem services to the region (Patz *et al.* 2005).

These new scientific results demonstrate the potential for losing many important ecosystem services, including some that are manifest across regional and global scales, as tropical forests continue to be cleared and degraded.

Summary and conclusions

This is a critical point in the history of the Amazon Basin, when human stresses could affect the ecology of the region for decades and centuries to come. Cross-disciplinary scientific research is particularly vital in helping us to understand how this crucial region functions, and how it may be changing. In response, one of the major priorities of the Brazilian-led Large-Scale Atmosphere Biosphere Experiment in Amazonia (LBA) has been to understand how Amazonia functions as an integrated entity, including interactions among terrestrial ecosystems, freshwater systems, and the atmosphere. Recent research stemming from the LBA, as well as other efforts, have already improved our understanding of human activities and their potential consequences for the sustainability of ecosystem goods and services in the basin.

Much of this increased understanding has resulted from remote sensing observations, intensive and coordinated field measurements, and synthetic modeling exercises. However, despite this new understanding, observational and modeling capabilities are still lacking. For example, there is a pressing need to observe smaller-scale patterns of forest degradation by increasing the spatial or spectral resolution of satellite observations (eg Asner *et al.* 2005; DeFries *et al.* 2005), and characterizing the fate of land use following clearing (eg Morton *et al.* in press). Others have suggested the need for monitoring changes in forest structure, possibly using active radar or lidar measurements (eg Drake *et al.* 2002; Lefsky *et al.* 2002). In the end, we must balance the need for these data, their cost, and competing needs for global environmental observation capabilities.

Recent assessments of the ecological impacts of land-use practices have focused on the need to balance the tradeoffs resulting from human actions (Millennium Ecosystem Assessment 2003; DeFries *et al.* 2004; Foley *et al.* 2005). In this framework, deforestation is recognized to have important benefits for society, as it increases economic opportunities and the availability of many ecosystem goods, at least in the short term. However, the loss of rainforests may also degrade many critical ecosystem services, such as carbon storage in forests and soils, regulation of water balance and river flow, modulation of atmospheric circulation and regional climate, and the amelioration of infectious diseases. Thus, the deforestation tradeoff is a balance between realizing short-term gains in selected ecosystem goods, while potentially degrading ecological function and other ecosystem services in the long term.

In this paper, we have distinguished between the local, regional, and global effects of deforestation, which also occur over a wide range of timescales, and the inherent tradeoffs they represent. While these cross-scale phenomena are increasingly recognized in ecology, it is important to note that each of these space and time scales (ie local- to global-scale, short- to long-term time horizons) have profoundly different effects on human society. Each ecological scale, in both space and time, potentially interacts with different groups of people, each with different levels of vulnerability and control.

Additional research is still needed to quantify the tradeoffs in ecosystem goods and services resulting from deforestation, and how they are manifested across local, regional, and global scales. Furthermore, continued efforts are needed to link the scientific quantification of ecosystem goods and services to policy-relevant terms, such as economic, political, or cultural valuation, allowing for multiple perspectives in the assessment of the consequences of deforestation.

The scientific community has made tremendous progress in understanding the continued loss and degradation of Amazonian rainforests, and their connections to human society. What we have learned is alarming, and reinforces the need to clearly communicate these new findings to stakeholders and decision makers across many levels.

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