Forest loss typically increases total annual water flows, potentially exacerbating chronic (but not necessarily catastrophic) flooding.

Juan Pablo Moreiras / Fauna & Flora International / Comisión Centroamericana de Ambiente y Desarrollo photo archive.

CHAPTER 4

Deforestation Imposes Geographically Varied Environmental Damages

What environmental problems are associated with deforestation—where and when do they occur, and who suffers from them? Forests have diverse environmental values and functions. This chapter unbundles those functions, which include provision of biological goods, maintenance of genetic diversity, regulation of water flows, and storage of carbon. The approach used here helps explain who suffers when those functions are impaired by forest degradation and the costs of maintaining or substituting for those functions.

This review is necessarily highly selective. The Millennium Ecosystem Assessment (2005), on which this report draws, provides a comprehensive synthesis of ecological relationships between forests and people. A motivation for that assessment, and for this report, is that social and economic policies often do not incorporate scientific insights. That shortcoming can result in poor prioritization of problems and poor choices of instruments for addressing problems. Two questions underscore this chapter's discussion: What are the most compelling reasons for reducing deforestation, and where do they apply?

Before starting the discussion, it is useful to offer a framework for thinking about environmental damages. The essence of environmental problems is the concept of an externality—where one person's actions unintentionally benefit or harm another person. For instance, I may remove the trees along my river banks, heedless that the consequent erosion will pollute your drinking water with sediment. In principle, society as a whole would be better off if externalities were factored into environmental decision making. If I gain $100 from felling my trees but you have to pay $1,000 to filter your drinking water, the potential damages from pollution far outweigh the potential profits from deforestation. There should be a way to arrange to keep the trees standing.

The nature of that arrangement depends on whether society assigns me the right to cut the trees or guarantees you the right to clean water. If the latter, your right trumps mine. My potential $100 gain is too little to compensate you for your $1,000 loss, so I won't bother to cut the trees. But if I have an absolute right to cut my trees, you would find it worthwhile to pay me up to $1,000 for the environmental service of preserving the trees and reducing erosion. Either way, the trees would remain standing. And the assignment of rights determines who benefits and who loses.

But there are transactions costs involved in enforcing rights and negotiating payments. Those costs can be high if there are diffuse sources of the externality and many on whom it impinges. Costs escalate further if sources and impacts are distant, with no shared institutions to help mediate the problem. Unfortunately, many of the environmental externalities associated with deforestation are characterized by a difficult combination of diffuse sources, diffuse impacts, and lack of intermediating institutions.

Biodiversity Loss—A Local and Global Concern

Biodiversity is an ambiguous term, and ambiguity can create confusion. The term is used in several senses. Sometimes it refers to biological resources: timber, fuelwood, fish, medicinal plants, pollinating bees. Sometimes it describes the diversity of microorganisms or cultivars within a plot of cropland. And sometimes it denotes the diversity of species, genes, or ecosystems considered from a local or global viewpoint.

These different senses of biodiversity all refer to valuable natural assets, and they overlap to some degree. But failure to distinguish between them can lead to conceptual and policy errors. For instance, there is evidence that diversity of rice cultivars within a farm plot increases yield and reduces costs. But that doesn't mean that conservation of plant and animal biodiversity in a nearby forest will necessarily boost productivity in a farmer's field.

Biological Resources Provide Locally Valuable Services

Local biological resources and local biodiversity are probably the aspects of forest biodiversity most immediately relevant to livelihoods and welfare. The most obvious benefits are related to extraction of biological resources such as fuelwood, timber, food, and fodder. These constitute a significant though inaccurately known share of income for people living in or near forests (see chapter 3).

Other local biodiversity services may be extremely important but inadequately recognized. According to Cassman and Wood (2005, p. 759) at least 80 percent of the world's 100 most important food crops are pollinated by wild pollinators. Ricketts and others (2004), in a study of Costa Rica, show that bees from forest fragments contribute substantially to coffee productivity and profits on adjacent farm plots—a pure, uncompensated externality. Forests may also support natural antagonists of crop pests. Or they may provide food for those beneficial creatures during the fallow season when there are no pests to feed on (Cassman and Wood 2005, p. 759).

These subtle relationships can be easy to miss—and easy to disrupt unintentionally. In principle, because most occur at a very local scale and contribute directly to livelihoods, it should be possible to set up local management institutions to handle them. In practice, these ecological benefits may not be immediately apparent to land managers, and solid scientific quantification is often lacking.

Extinction Threats Draw Attention to Globally Significant Biodiversity

This chapter focuses on conserving globally significant biodiversity: genes, species, and ecosystems at risk of extinction. Given the global nature of the externalities involved, this is a serious challenge. Conservation of globally significant biodiversity is motivated by the growing threat of irreversible loss. According to the Millennium Ecosystem Assessment (2005), current extinction rates are about 100 times the rate they were before humans existed and could increase by another 10–100 times.

There are two reasons for the world to be concerned about this looming, irreversible loss. The first is instrumental: conserve biodiversity because it provides specific economic services or averts specific risks. The second is intrinsic: conserve biodiversity because people attach aesthetic and spiritual values to it, or because their values demand it. Proponents of this rationale justify conservation of diversity as an inherent goal, of the same kind as reducing child mortality or preserving the great artworks of earlier civilizations.

Can conservation of globally significant biodiversity be justified on instrumental grounds? Many valuable pharmaceutical products are derived from tropical plants. But this has so far failed to spark a significant market for bioprospecting rights: drug companies have not been willing to pay much for the right to prospect in particular areas. Simpson, Sedjo, and Reid (1996) provide a convincing explanation for why. A standard approach to bioprospecting is unfocused—simply hoping that randomly selected organisms will yield promising chemicals for treatment of target diseases. But given a low rate of success and substantial overlap in genetic contents between forest plots, no individual plot is unique enough to command much of a premium. Drug companies could continue to find ample specimens for evaluation, for decades to come, even with rapid deforestation. Accordingly, such bioprospecting has failed to provide sufficiently "bankable" benefits to pay for conservation.

Better-focused bioprospecting might confer higher economic values for conservation. For instance, forests that harbor the wild relatives of commercially exploited species such as coffee, vegetables, and fruits might be an enduring source of useful genetic information for global agriculture, including information about pests and their natural enemies. More systematic searches for particular kinds of biological activity, combined with better information about biodiversity distribution, might generate high bioprospecting rents for particular locales.

Finally, the Millennium Ecosystem Assessment (2005) argues that biodiversity loss and associated large changes in forest cover could trigger abrupt, irreversible, harmful changes. These include regional climate change, including feedback effects that could theoretically shift rainforests to savannas; and the emergence of new pathogens as the growing trade in bushmeat increases contact between humans and animals.

These instrumental arguments for conserving global biodiversity are still rather speculative and unfocused. In contrast, the intrinsic rationale for conservation—conservation as a fundamental value—has deep resonance in ethics, aesthetics, and religion. These different approaches lead to a formulation of biodiversity policy that places an "existence value" on maintenance of diversity. Surveys suggest substantial willingness to pay for this diversity, at least in industrial countries, though the validity of these stated preferences has been questioned. Funding for the Global Environment Facility and for large, conservation-oriented nongovernmental organizations (NGOs) is a palpable demonstration of willingness to pay.

The science of biogeography provides important insight into the design and geographic targeting of forest policies aimed at reducing extinctions. First, biogeography tells us that species and other aspects of biodiversity are unevenly distributed across the Earth (Mace, Masundire, and Baillie 2005, pp. 90–91). Species of vertebrates are much richer near the equator. Endemic species (those with limited ranges) tend to cluster on islands and mountaintops. And an analysis of biodiversity hotspots has found that half the world's vascular plant species are located on just 1.4 percent of Earth's land surface (Myers and others 2000). Other conservation scientists emphasize the desirability of preserving places with distinctive ecological processes, such as mass migrations of wildlife, or locations that appear to be generating new species (Burgess and others 2006).

Second, one of the most well-established regularities in ecology links habitat area to number of species in the habitat. As habitats shrink, there are fewer niches for specialized species, and there is less room for predators that need large ranges to maintain viable populations. As usually formulated, a 90 percent reduction in area is associated with about a 30 percent reduction in the number of supported species. For an optimist, this is not too bad a result: the mostly empty glass is still, in effect, more than half full. Conserving just 10 percent of the original forest biome could theoretically maintain more than half of its original biodiversity.

Third, however, forest fragmentation further reduces the survival prospects of species and their ecosystems. Relative to a large chunk of forest, small chunks with the same total area are more exposed to natural and human pressures such as wind, fire, and hunting. Forest-specialist species requiring large contiguous blocks of habitat fare poorly in fragments that are widely scattered through an inhospitable matrix of fields or settlements (Laurance and others 2002). As fragmentation increases and connectivity weakens, prospects for these species get dramatically worse (box 4.1).

Fourth, extinctions respond with a lag to loss of habitat. The relation between species and area holds over the long run. Places that have suffered rapid habitat loss may still contain their original complement of species, but may not be able to for much longer. Brooks, Pimm, and Oyugi (1999) estimate that a newly isolated 1,000 hectare fragment experiences about half its eventual species

Box 4.1 Forest Fragmentation Can Trigger Local Ecological Collapse

Imagine a checkerboard arrangement of forested properties or plots of land in an area that is a biodiversity corridor. Initially the land is entirely forested, and a key animal species is free to roam from one side to another. Then settlers arrive and randomly convert some properties to fields that are inhospitable to the animal. How does the amount of converted land affect the animal's ability to traverse the corridor?

A remarkable mathematical result is that the animal can *always* find a path when the proportion is below 41 percent, but *never* when the proportion is above that threshold. Although this is a highly stylized result, it points to the possibility of rapid and unexpected ecological collapses as deforestation proceeds. It also underscores the potential importance of landscape-level management for biodiversity in places where forests and farms are intermixed. Farm-level decisions about cropping, maintenance of gallery forests, and establishment of living fences can make a big difference for biodiversity conservation.

Source: Based on Forman 1995.

losses in 50 years. Rosenzweig (2001, 2003) takes a longer, starker view. He says that in the very long run, species loss is proportional to habitat loss because climate and disease shocks continue to cause extinctions, while the rate of creation of new species is proportional to habitat area. So he argues that a 90 percent habitat loss implies an eventual 90 percent species loss. He doesn't specify whether that adjustment takes centuries, millennia, or longer.

Finally, the rapid pace of climate change provides another reason why connectivity is important, and why Rosenzweig's drastic adjustment may come sooner rather than later. Plant and animal species are adapted to particular temperature ranges. As global temperatures rise, the survival of some species will depend on their ability to migrate to cooler areas, on higher slopes, or at higher latitudes. If there is insufficient connectivity in existing habitats, these species may be unable to migrate and will get caught between rising temperatures and inhospitable surroundings. Climatically triggered diseases could make things worse.

This foray into biogeography provides important policy lessons.

- Conservation of globally significant biodiversity requires focusing attention and resources on certain places. This approach may clash with other norms for allocating resources between countries and places. A country's share of global biodiversity, for instance, may differ from its share of global population or poverty.

- The most urgent extinction threats will largely be in and around fragmented mosaiclands where habitat has drastically shrunk and become fragmented. Here, species and ecosystems are living on borrowed time. There is a brief opportunity—the next few decades—to refurbish these landscapes and make them more habitable to most threatened species, while maintaining their usefulness for agriculture and human habitation (McNeely and Scherr 2003; Rosenzweig 2003). Reducing fragmentation and encouraging connectivity are important parts of this program.
- Threats are low in large, unfragmented forest tracts. But these species-rich areas are the last irreplaceable examples of large-scale ecological processes in quasi-natural habitat. They also offer insurance against climate change, allowing species uninterrupted pathways for migration in response to rising temperatures. Policy interventions today to head off a dynamic of uncontrolled conversion could determine whether, over the coming century, these tracts retain ecological vitality or whether they grow fragmented, placing their species at threat of extinction.

How Does Deforestation Affect Water, Air, and Weather?

Clean water flows from forested hillsides, muddy torrents from steep denuded slopes. These observations have often been used reflexively to justify forest conservation. But in recent decades scientific research has refined people's understanding of how forests and land use affect flooding, sedimentation, landslides, and dry season flows. Although some aspects of these relationships remain debated, the overall message is clear: the forest-hydrology relationship is highly nuanced. The effects on hydrology of changes in forest and land use depend, systematically and explicably, on how and where changes occur.

It is important to get the science straight. For instance, Aylward (2005) reports on a study of the potential effect of reforesting pasturelands around Costa Rica's main hydropower reservoir to reduce sediment inflow. The study found that reforesting 1 hectare would reduce sedimentation and estimated the benefit, in increased reservoir life span, to be $74 per hectare reforested. But the study also found that higher water consumption by the trees would draw down the reservoir—imposing potentially larger, countervailing costs due to decreased electric output during dry years.

Consider too the diagnosis of the catastrophic 1998 floods on China's Yangtze River. The floods were blamed on deforestation, and a swift policy response was the shutdown of the Chinese logging industry. This move disrupted domestic employment and placed increased extractive pressures on forests of high biodiversity significance in Southeast Asia and elsewhere. But to what extent was deforestation to blame?

Subsequent analysis suggests a complex picture (Yin and Li 2001). Beginning with the construction of the Great Jinjiang Levee in 1548, and accelerating in the past 50 years, many land use changes have reduced the ability of the Yangtze watershed to handle peak water flows. The flows, which formerly covered vast floodplains, have increasingly been constricted by levees and dikes. Since 1949, 50 cubic kilometers of lakes have been reclaimed for agriculture, reducing lake storage capacity by a third and thus crippling a major buffer against flooding. Heavy siltation has raised the river bed, increasing the risk of flooding. Deforestation and other land use changes have increased the proportion of the basin subject to erosion, and so over the long run have presumably contributed to siltation. But observations over a 30-year period did not show any link between siltation and deforestation, suggesting that it may take decades for erosion to end up as sediment in the river. Thus in the context of the complex hydrodynamics of a large basin, it is not at all clear to what degree the logging ban has reduced the risk of future floods or how it compares to alternative watershed management strategies.

To help get the science straight, this section relies heavily on comprehensive and incisive reviews by Bruijnzeel (2004) and Bruijnzeel and others (2005). It also draws on Bonell and Bruijnzeel (2005), Calder (2005), CIFOR and FAO (2005), and van Noordwijk and others (2006). Interested readers can refer to these works for more detailed treatment.

From Farmer's Field to River Basin: Policy at Different Scales

Interactions among people, precipitation, soils, and vegetation play out differently at different scales. First, many phenomena important at smaller scales become attenuated at larger ones (Kiersch and

Tognetti 2002; Calder 2005). Consider erosion and sedimentation. Erosion can be severe on steep fields, clogging local streams with sediment. At this scale, actions to prevent erosion and sedimentation can have more or less immediate effect. But at the level of a large watershed, new upland erosion doesn't translate immediately to sedimentation far downstream. This is because any individual bit of sediment has to follow a long journey of short trips from mountainside to river mouth. That journey could take decades—or it may never be completed—because the sediment gets lodged somewhere along the way (Chomitz and Kumari 1998).

Second, the economics and politics of watershed management vary with scale. In small watersheds (10–100 square kilometers) it may be relatively easy to organize local communities to deal with clearly perceived issues such as erosion or landslide risk. Larger basins require more complex, wide-ranging institutions to negotiate interests between upstream and downstream populations. But the payoffs to cooperation at this scale might be considerable. Urban populations might be willing to pay substantial sums to reduce flood risk, sediment damage to reservoirs, or pollution of urban water supplies. If they could do so by paying poor upland populations to conserve forests, it would be a happy outcome on many grounds: reducing flooding and poverty, with biodiversity conservation as a by-product.

Against this background, consider how changes in forest cover and land use affect hydrological functions that people care about, at two scales: local and far-field.

Local Hazards Depend on Many Variables

Forests modulate water flows in various ways. In the popular conception, trees are sponges, soaking up water and releasing it later. But this is an inadequate and incomplete metaphor (Bruijnzeel 2004). Forest floors, with their leaf litter and porous soils, easily accommodate intense rainfall. Water infiltrates the ground until soils are saturated. In this sense forest soils act like sponges. But trees behave like fine-misted fountains, pumping water out of the ground and transpiring it as water vapor into the air.[1] Rain also clings to tree leaves, from which it evaporates without ever touching the ground. The effects of deforestation on water availability, flash floods, and dry season flows depend on what happens to these countervailing influences of infiltration and evapotranspiration—the sponge versus the fountain.

Replacing a mature forest with a mature agroforest doesn't much change evapotranspiration and so has little effect on water yield. But permanent conversion of forest to pasture, annual crops, or short perennial crops reduces evapotranspiration and thus increases the water yield from a plot. On this point there is strong scientific consensus. Converting a tropical moist forest is roughly equivalent, in water yield, to increasing rainfall by 300 millimeters a year. That's why South Africa's Working for Water program pays for the removal of invasive tree species—to increase water availability in parched regions. The program employs 21,000 poor people and provides water to Capetown at a cost 90 percent below the alternative: construction of a dam (van Wilgen and others 2002).

Floods and Flow Regularity

Deforestation's effect on the timing of flows—on floods and dry season flows—is more difficult to predict and is sensitive to the balance between infiltration and evapotranspiration effects. Deforestation tends to increase flooding for two reasons. First, with a smaller "tree fountain" effect, soils are more likely to be fully saturated with water. The "sponge" fills up earlier in the wet season, causing additional precipitation to run off and increasing flood risk. Second, deforestation often results in compacted soils with little ability to absorb rain. Locally, this causes a faster response of streamflows to rainfall and thus potential flash flooding. That is why some Costa Rican run-of-river hydropower plants invest $1.50–5.00 in watershed protection per kilowatt generated each year (Rojas and Aylward 2002). These small plants (6–17 megawatts) have no storage reservoirs, so their output is greatest when water flows evenly at their turbines' capacity.

Dry Season Flows

More controversial is the impact of deforestation on dry season flows. Here there is strong divergence between the popular view that deforestation dries up springs, and scientific evidence that strongly indicates higher—not lower—flows after deforestation. A thorough review by Bruijnzeel (2004) finds only a couple documented cases of lower flows. But he stresses the need for more observations. In theory, deforestation could decrease dry season flows under certain conditions:

- New land use patterns result in severely compacted soils, so losses of rain to runoff exceeds gains from shutting off the "fountain" (Bruijnzeel 2004). This might happen where cattle or machinery have caused severe compaction, where there has been extensive road building, or where fires have degraded the landscape. In other words, postdeforestation land use matters more than just deforestation.

- Annual rainfall is high and concentrated in the wet season.
- Soil has considerable water holding capacity or is in an important recharge zone.

Sedimentation and Erosion

Think about sediment, and you will understand why watershed management involves more than simple decisions about how many trees to retain or plant (Van Noordwijk and others 2006). First, people place different values on sediment. Reducing sediment is a service to downstream irrigators, reservoir owners, and water filtering plants—but not to farmers who depend on it for renewed soil fertility.

Second, deforestation doesn't necessarily increase erosion, the main source of sediment. As with flooding, what matters is how land is used after forest is removed, and especially whether leaf litter is maintained. Typical erosion rates are 0.2 tons a hectare under forest and 0.6 under plantations with ground cover, but more than 50 tons a hectare may be observed under plantations without leaf litter (Wiersum 1984, quoted in Bruijnzeel 2004). Forest roads generate far more erosion per hectare than do agricultural uses. Ziegler and others (2004), in a study of a northern Thai watershed, found that unpaved roads delivered as much sediment to streams as did agricultural fields—though the fields occupied 24 times more area.

Third, the spatial arrangement of land use matters. Van Noordwijk and others (2006) simulated the effect on sedimentation of different combinations of clean-weeded coffee plantation and forest on a Sumatran hillslope. Retaining 25 percent forest at the bottom of the slope reduced sedimentation by 93 percent relative to no forest. Forest retention elsewhere on the hillslope was much less effective. In sum, watershed management for sediment reduction involves many choices, with different consequences for incomes, biodiversity, and other environmental outcomes.

Landslides

Forests can provide protection against shallow landslides. Perotto-Baldiviezo and others (2004) studied the incidence of landslides after Hurricane Mitch in a Nicaraguan watershed. They found that less than 1 percent of forested lands were affected by landslides, regardless of slope. For plots under bare soil (recently harvested) this incidence jumped from near zero on flat land to 7.5 percent on land with

10 percent slope, and 10 percent when slope was 20 percent. But some deep-seated landslides occur regardless of forest cover.

Water Quality

Urban water protection is potentially one of the most important services that forests provide. Filtering and treating drinking water is expensive. Forests can reduce the costs of doing so—either actively, by filtering runoff, or passively, by substituting for housing or farms that generate runoff. An example is New York City's watershed (National Research Council, Water Science and Technology Board 2004, pp. 156–58). For many decades the city had drawn its water, untreated, from its 5,000 square kilometer watershed. In the mid-1990s water quality began to deteriorate, and authorities were faced with the prospect of committing $6–8 billion (in operating and future maintenance costs) for a treatment plant to meet safety standards.

Instead the city developed an innovative program for watershed protection, at a cost of $1.0–1.5 billion. About $250 million was used to purchase and protect land (though not necessarily forestland). But the plan also involved activities to reduce water pollution. Importantly, it worked with dairy farmers to manage manure and nutrient runoff.

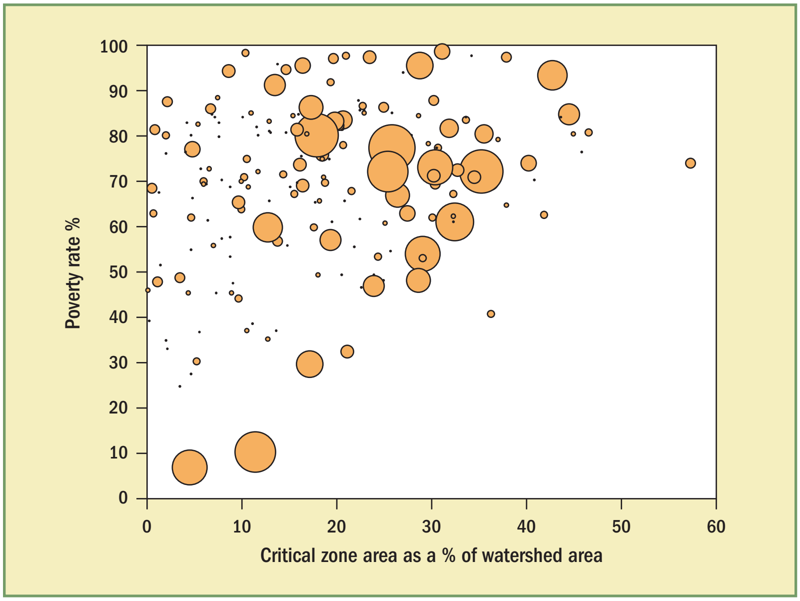
This example may be widely applicable. Dudley and Stolton (2003) found that 18 of the world's 42 largest tropical cities draw their water directly from protected areas. An extension of this study might usefully identify cities that draw their drinking water from small, steep, forested watersheds. Under these conditions the public value of watershed protection is likely to counterbalance private rewards to forest conversion or degradation.

Geography of Local Hazards

Nelson and Chomitz (2006) examine the potential spatial coincidence of local hazard risk and poverty in two hilly Central American countries, Honduras and Guatemala. The authors define a watershed's critical zone as where forests meet agriculture on slopes. This is where deforestation might be most rapid and might lead most rapidly to erosion. They then define a watershed's "sensitivity" as its proportion in a critical zone.

In Guatemala highly sensitive watersheds (more than 20 percent critical) occupy 22 percent of the country but contain 43 percent of its poor people and 54 percent of its montane forest. The poverty rate in these watersheds is 70 percent, compared with 53 percent for

Figure 4.1 Guatemala Critical Watersheds Have High Poverty Rates



Source: Nelson and Chomitz (forthcoming).
Note: Bubble size indicates absolute number of poor people in watershed.

the country as a whole. Figure 4.1 shows that all of the most sensitive watersheds have high poverty rates. Nelson and Chomitz (2006) also find that the relationship between hydrological vulnerability and poverty is stronger when smaller watersheds are considered. This focuses attention on highly local externalities, with poor people both causing them and bearing their burden.

At the global scale, Dilley and others (2005) used topographic and geological criteria to identify areas around the world at risk of landslides. Areas with the highest imputed mortality risk from landslides—including along the mountainous spine of Latin America, the islands of Sumatra, New Guinea, and the Philippines, and the border between India and Myanmar—are shown in map 4.1.[2] Because mountain peaks tend to host distinctive, restricted range species, the landslide risk map is strikingly similar to the imminent extinctions map (see map 1.8).

Far-field Impacts Can Be Major

We turn now from local impacts of deforestation to far-field impacts—those felt tens or hundreds of kilometers away.

Distant Floods

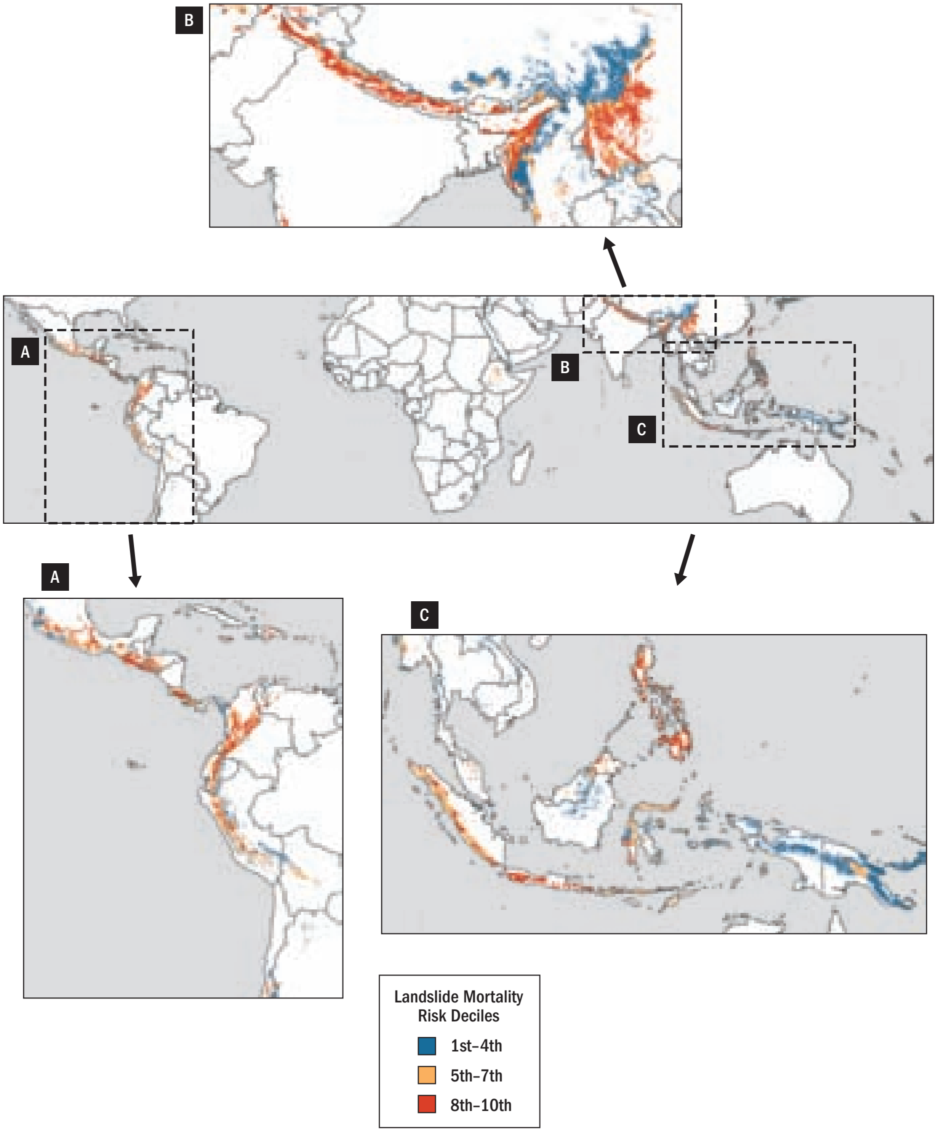
Because urban floodplain populations are growing rapidly, human and economic exposure to flood risk is growing as well. But some hydrologists doubt whether large-scale upstream deforestation has much impact on distant downstream populations. They argue that small rainstorms, passing over a large river basin, affect only one tributary at a time, so any flooding effect is diluted by the time it reaches a city down the river's main branch. The rare storm large enough to drench the entire basin, they argue, would probably overwhelm the basin's ability to absorb water into the soil. A storm that big would cause a flood regardless of tree cover.

This argument is hard to test. There are two ways to study links between deforestation and floods in large basins: through long-term historical studies and by simulation. Each has limitations. Historical studies may face confounding trends—such as increases in irrigation or construction of dams—with impacts that are difficult to disentangle from those of deforestation. Simulation studies are sensitive to the reliability and detail of data on rainfall, soils, and river flows.

Historical studies yield contrasting results. Several studies reviewed by Bruijnzeel (2004), mostly in Southeast Asia, found no marked increase in river flows following basinwide deforestation. In contrast, Costa, Botta, and Cardille (2003) found a substantial impact on far-field flows of deforestation in the 175,000 square kilometer Tocantins River basin. They compared flows over 1949–68 and 1979–98. Only 6 percent of the basin had been converted to planted pasture or cropland in 1960, but by 1995 it was 49 percent. The study found that, despite similar rainfall, wet season river flows increased 28 percent between the two periods. The authors speculate that the difference between their results and those in Southeast Asia reflect the faster natural regeneration in the Asian study areas. A change from primary forest to plantations or secondary regrowth may have little effect on hydrological flows (though possibly a profound effect on biodiversity).

Because it is hard to isolate the effect of long-term, large-scale changes in land use through observations, researchers have turned to hydrological simulations. Advances in hydrological modeling have resulted in tools that can reproduce watershed behavior with some accuracy, such as the Distributed Hydrology Soil Vegetation Model (Wigmosta, Vail, and Wittenmaier 1994). These models trace water and sediment flows over the landscape, incorporating effects of vegetation and geology. Their accuracy is validated by comparing model predictions, based on historical precipitation records, with streamflow records.

Map 4.1 Mortality Risks from Landslides



Source: Dilley and others 2005.

Scientists are beginning to use these models to assess the impacts of land cover change in the tropical world. An example is Thanapakpawin and others (2006), who constructed and validated a model of the 3,853 square kilometer Mae Chaem watershed (in northern Thailand) using limited data on soils and precipitation. The authors used the model to assess, retrospectively, the impact of the loss of about 10 percent of the watershed's forest cover. Other things being equal, they found that deforestation would have increased wet season flows by 2 percent and dry season by 4 percent. But expanded irrigation more than counterbalanced the deforestation effects, reducing net outflows by up to 6 percent in the wet season and 16 percent in the dry. Ongoing work extends this to larger basins and shorter periods.

Douglas and others (2005, forthcoming) have conducted similar simulation studies in large river basins throughout the tropics. Their work seeks to determine whether and where forest losses would have significant effects on biodiversity and water flows. For this purpose, they simulated the hydrological impacts of the complete conversion to agriculture of all forests deemed "critical or endangered" by WWF.[3] They calculated the resulting change in river flows and identified areas that would be expected to experience an increase in mean annual flows of more than 25 percent. The assumption was that increases of this magnitude could be associated with chronic if not catastrophic flooding. (The exact impact is highly sensitive to the local geography of the floodplains and to daily and hourly peak flows.) The authors found that the hypothetical catastrophic loss of these forests would increase annual river flows by more than 25 percent for about 100 million people, most of them on floodplains. In nine basins containing 55 million people, more than 100 people would be affected by each square kilometer of forest conversion—a crude indicator of the potential for mobilizing downstream interest in upland forest conservation.

The hydrological cost-effectiveness of forest protection might be increased by concentrating on hydrological hotspots—those where deforestation might have the greatest downstream impact. Combining spatial models of deforestation and hydrological functions could help pinpoint these locations.

Water Quality

Does it make sense to manage land over a very large basin to reduce sedimentation for downstream users? Although sediment travels slowly over slopes, it can be mobilized fairly rapidly from riverbanks over a wide area. A simulation study found that sediment load in a 2,500 square kilometer watershed could be cost-effectively reduced by revegetating steep croplands close to the river (Khanna and others 2003). Although this finding sounds obvious and mirrors the local area results noted earlier, it contrasts with a strategy of protecting forested uplands far from major rivers. In generalizing this analysis, it is important to keep in mind that vegetation other than trees can intercept sediment without using as much water as trees do.

Effects on Air and Climate

Forest fires release noxious smoke and smog, disrupting transport and industry and triggering respiratory illness. These are chronic problems. In Brazil smoke from forest and land fires is cited as a major environmental problem by *municipio* governments that represent 39 million people. These problems are worst in dry (El Niño) years. Tacconi (2003) estimates that the Indonesian fires of 1997–98 affected 110,000 square kilometers in Indonesia and Malaysia, imposing costs in damaged health and industrial disruption of $676–799 million.

Deforestation affects wind flows, water vapor flows, and absorption of solar energy, so it's plausible that it affects local climate. But it's difficult to assess these impacts, which may operate differently at different scales, from field to continent. One study found that deforestation on lowland plains moved cloud formation and rainfall to higher elevations (Lawton and others 2001). Another study found strong changes in land-sea breeze patterns affecting cloud formation and upland rainfall in tropical island and coastal settings (van der Molen and others 2006). Yet another study simulated the impact on regional climates of a plausible scenario for global deforestation during this century. It predicted that Amazônian temperatures will rise by 2 degrees Celsius, in addition to effects from global warming. It also predicted possible disruptions of Asian monsoon patterns (Feddema and others 2005). Finally, van der Molen and others (2006) and other researchers intimate the possibility of global impacts of widespread deforestation—especially for coastal and island deforestation, which disrupts atmosphere-wide wind patterns.

Deforestation Spurs Climate Change

There's no need to repeat here the vast literature on climate change; for authoritative summaries, see the work of the International Panel on Climate Change (Watson and Core Writing Team 2001) and the Millennium Ecosystem Assessment (2005). Still, three points are crucial.

First, climate change is a real and growing threat to people, economies, and the environment. Arctic communities already face permafrost that is no longer permanent. Andean populations need to begin planning for the impending loss of glacial icepacks on which their water supply depends. Poor Sahelian farmers and pastoralists, already coping with a difficult and volatile climate, may soon experience deteriorating conditions. Looming behind the predictable threats, however, is the real but unquantifiable possibility of rapid, catastrophic changes—such as a shutdown of Atlantic Ocean currents or massive changes in regional climates.

Second, tropical deforestation is an important source of greenhouse gases, releasing 3.8 billion tons of carbon dioxide (CO_2) a year (Achard and others 2004). Such deforestation also accounts for about 20 percent of human-generated CO_2 emissions (House and others 2006).

Third, preventing deforestation and encouraging forest regeneration have the same effect on atmospheric CO_2, no matter where they occur. This is in marked contrast to other environmental benefits of forest conservation, which depend on local conditions.

Forest management has global effects on greenhouse gases. But does it make economic sense to actively manage forests to reduce atmospheric CO_2 emissions (box 4.2)? What might be the costs and benefits to landholders? How do the costs of reducing CO_2 through forest management compare with those of abating CO_2 emissions from transportation, electricity generation, and manufacturing?

Consider first the cost of reducing CO_2 emissions from deforestation. The cost to landholders depends on:

- The per hectare profits forgone by maintaining forest rather than converting it.
- The difference in carbon storage between a conserved forest and a field or pasture.

These two considerations vary tremendously depending on the factors discussed in chapter 2: agroclimate, market opportunities, and technology. Rigorous data on these trade-offs have been assembled by the Alternatives to Slash and Burn program for a number of land use systems in the moist forests of Brazil, Cameroon, and Indonesia (Tomich and others 2005). For each land use, researchers calculated the net present value of profits (a measure of the value of land devoted to that use), the amount of carbon stored, and the level of biodiversity conserved.

Drawing on these data, figure 4.2 shows the implicit costs of reducing carbon emissions through forest conservation. These costs were calculated by comparing the profits and carbon storage of each

Box 4.2 Trees and Carbon: Lessons from Biology for Forest Policy

Many of us vaguely remember learning, in a biology class long ago, that trees absorb carbon dioxide (CO_2) and produce oxygen. But that's only part of the story, because trees also use oxygen for respiration and release CO_2, just as animals do. A growing tree absorbs more CO_2 from the atmosphere than it emits, embodying the carbon as wood, leaves, and other biomass.

A tree that dies, or is cut down, rots or burns. The carbon in its biomass is then released into the atmosphere as CO_2. Soil carbon may also be exposed and lost into the atmosphere. In a regenerating forest, growing trees outnumber dying ones, so carbon accumulation is vigorous. But as forests mature, their net accumulation of CO_2 slows. (There are debates about the rate at which old-growth forests continue to sequester carbon.)

What does this mean for the impact of alternative land uses on carbon storage?

- Converting forests to agriculture or pasture releases CO_2 into the atmosphere, so protecting a threatened forest could reduce greenhouse gas emissions.
- Mature standing forests maintain carbon stocks, but have at most a low per hectare rate of accumulation.
- Reforestation and afforestation absorb CO_2 out of the atmosphere, storing it as wood and biomass as long as the forest endures.
- Pulp and timber plantations absorb CO_2 as they grow. The carbon they embody is transformed into wood or paper after harvest. It may be released rapidly into the atmosphere if these products are discarded or incinerated. But timber used for enduring structures may stay out of the atmosphere for a long time.
- Plantations can create fuel from thin air by absorbing CO_2 and transforming it to biomass. When burned as charcoal or biofuel, the same amount of CO_2 is returned to the atmosphere, in a closed cycle. So sustainable biofuel plantations are carbon neutral—they don't add net CO_2 to the atmosphere—and can substitute for fossil fuels, which do augment global warming.
- Logging releases CO_2 from damaged trees, though forest recovery may partly offset this effect over time. The harvested timber may release its carbon quickly to the atmosphere, if burned or discarded to rot, or slowly if used for construction.

land use system and an assumed forest baseline. (The Cameroon and Indonesian examples assume a baseline of already logged, depleted forest.) The figure shows the tremendous variation in the potential costs of conserving carbon.

At one extreme, traditional pasture management in Acre, Brazil, entails a loss of 145 tons of carbon per hectare but creates only $2 a hectare in land value (in net present value of all future earnings). So the cost of conserving carbon is, in principle, just $0.03 a ton C (or less than \$0.01 per ton of CO_2). Similarly, traditional rubber agroforestry in Indonesia provides lower per hectare profits and a significant loss of carbon relative to community agroforestry—although it creates much more employment. In contrast, the most profitable land use, for intensive cocoa in Cameroon, entails a carbon loss of 103 tons per hectare, confers a land value of \$1,149, and provides 93 days of employment. Here the theoretical cost of conserving carbon is \$11 a ton (\$3/ton CO_2).

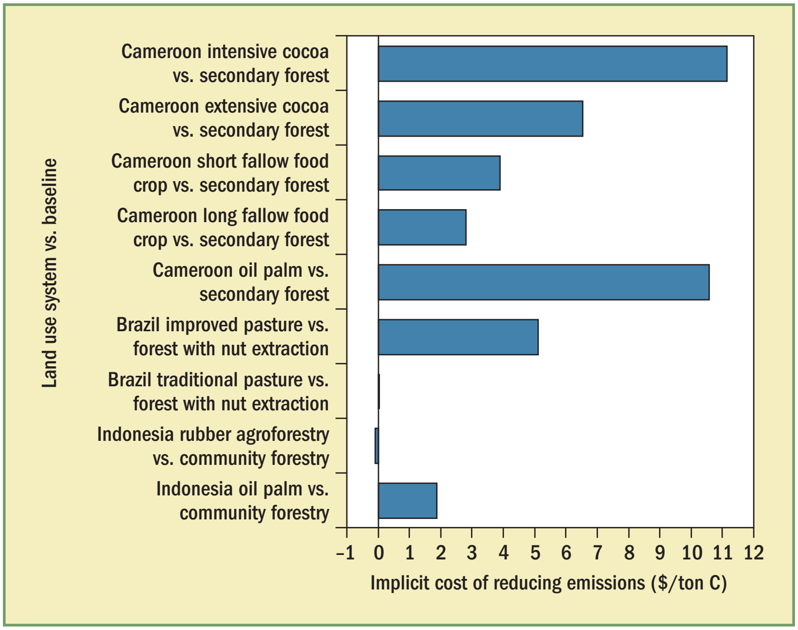
These calculations assume that the costs are borne by landholders, in forgone profits, and that workers can find alternative employment at the same wage. This may be a reasonable assumption when deforestation is related to frontier migration. Otherwise, workers bear a burden—because of lower-paying work—that should be included when calculating the cost of emission reductions.

For extensive land uses this makes little difference. Traditional Brazilian pasture, for instance, provides only 11 days of employment a hectare per year. But rubber agroforestry, intensive cocoa, and intensive palm oil provide about 100 days of employment, at roughly \$1.50 a day. Counting a portion of this as a cost would somewhat increase the cost of conserving carbon.

One way of looking at these calculations is to ask whether society should incur these costs. Are they justified by the benefits from mitigating climate change? Making this assessment requires assigning a value to abating emissions. Yohe, Andronova, and Schlesinger (2004) suggest that to mitigate climate change, the global community needs to value carbon abatement at \$10 a ton now (and rising over time based on the interest rate). At that value, converting forest to intensive cocoa barely breaks even from a social viewpoint—though from a private viewpoint it is the most profitable land use shown in figure 4.2.

Efforts are under way to scale up estimates of this type to the global level. These estimates must be considered tentative, because comprehensive information on land use systems is lacking. Still, the estimates are useful for assessing the potential scale of the contribution of land management to carbon abatement. Sathaye and others (forthcoming) estimate the potential contribution of avoided deforestation to carbon abatement for different levels and trends of carbon prices. (Anticipating the discussion in chapter 7, imagine that per hectare monetary incentives are offered to nations if they reduce planned forest conversion.) Relatively modest carbon prices (\$5–10 a ton in 2010, rising 5 percent a year) could, in principle, deter con-

Figure 4.2 Deforestation Would Be Unprofitable in Many Land Systems at Modest Carbon Prices



Source: Authors' calculations using data from Tomich and others 2005.

version of 1–2 million square kilometers of forest by 2050, preventing the release of 8–15 billion tons. A price of $100 per ton of carbon would induce conservation of 5 million square kilometers by 2050, abating the release of 47 billion tons.

Forest Loss—Sometimes Irreversible

In an uncertain world, it's good to have options. Even if an option isn't worth exercising today, there's a chance it may be worth a lot tomorrow. That possibility is enough to give the option real value today. The theory of options finds sophisticated application in financial markets and investment decision making. It also applies to forests.

A forest owner has two options: converting the forest to agriculture or maintaining it. In some cases conversion is irreversible, so individuals and nations need to exercise this option wisely.

Sometimes deforestation is reversible. Deforestation for extensive pasture, subsistence cropping, or perennial crops is often followed by field abandonment and spontaneous regrowth. Regenerated forests often recover their biomass and carbon content and the species richness of the original forest—though some or much of the original biodiversity may be lost. That happened in Puerto Rico, which lost nearly all its forest only to see it rebound. Carbon densities are now nearly at their original levels, and species diversity is high. But the set of species has changed, with some of the originals lost (Lamb, Erskine, and Parrotta 2005a).

But sometimes the outcome is the worst possible: deforestation for short-lived, low-value agriculture or extraction, followed by degradation to a persistent, low-biodiversity, low-carbon grassland or shrubland. These degraded lands do not spontaneously revert to forest, though regeneration can sometimes be induced (Chazdon 2003; Lamb, Erskine, and Parrotta 2005). This destructive pattern can result from "vicious circles"—especially those involving fire (Cochrane and others 1999; Nepstad and others 2001).

Deforestation results in fragmented forests with high ratios of edge to area and greater exposure of soil to direct sunlight—leading to drier soils and greater susceptibility to wild and anthropogenic fires. Fires result in higher fuel loads, further increasing susceptibility. Repeated fires favor the growth of grass and inhibit forest regeneration. Smoke may also inhibit rainfall, further drying out the soil and increasing flammability (Nepstad and others 2001). The result, in Latin America, southern Africa, and Southeast Asia, is a relatively stable grassland system with no tendency to revert to forest (Lamb, Erskine, and Parrotta 2005a). Another vicious-circle mechanism involves loss of mammals that disperse large seeds. In Madagascar, for instance, lemurs are important seed dispersers. Fragmented forests support fewer lemurs; fewer lemurs means less dispersal of tree seedlings and hence more fragmentation of forests.

These degraded areas cover an appreciable portion of the Earth's surface. *Imperata* grasslands in Southeast Asia are estimated to cover about 350,000 square kilometers (Garrity and others 1996), a bit less than the area of Paraguay. Degraded areas are thought to be large in parts of Latin America. For instance, in long-settled parts of the eastern Amazon, extensive tracts are reported abandoned but unused and appear to be the degraded remains of former forests.

Ecologists have identified risk factors for persistent degradation (Chazdon 2003; Lamb, Erskine, and Parrotta 2005a). Geographic risks include areas with poor soil fertility and high susceptibility to erosion, due to soil or slopes. Risks are also related to the cause and conduct of deforestation. Soil compaction from bulldozing or cattle is an important risk. So are repeated fires. Large expanses of deforestation contribute to irreversibility, because natural reseeding is vigorous only within 100 meters of existing forest. Low-productivity pastures—characterized by fire use, compaction, and large clearings—may be at particular risk of irreversibility. They represent a particularly bad bargain: low and temporary returns, little employment generation, large environmental damage, and high probability of irreversibility.

Summary

Environmental externalities associated with forests are diverse, unevenly distributed, and understood with varying degrees of scientific consensus and precision. Table 4.1 arranges environmental externalities in rough order of scale of impact, from global to local. It shows that, carbon aside, most externalities are generated by distinctive and often narrow places and circumstances, ruling out one-size-fits-all responses. Most cases involve different people at the sending and receiving ends of the externalities. Mosaiclands are a hotbed of externality-generating forests, reflecting their rapid deforestation and the close interaction between forests, agriculture, and people in these areas.

Carbon emissions and extinction risk rank at the top of the list of globally important externalities. Returning to the example that opened this chapter, this opens a path for the global beneficiaries of forest conservation to compensate those who bear its costs. For instance, a serious global commitment to implementing the Framework Convention on Climate Change—which calls for stabilizing greenhouse gases in the atmosphere—would imply benefits for forest conservation that exceed the profits of most current forest conversion processes. Chapter 7 explores the implications of the forest-carbon connection for global policy.

The hydrological impacts of deforestation are extremely sensitive to local conditions. In the past, policy was influenced by hydrological myths, such as the one that forests generate water. Reliance on these myths has led to reforestation with perverse outcomes and may have undermined efforts to mainstream forest protection.

Current knowledge suggests that the highest payoff to watershed management occurs within small watersheds, in small steep basins

Table 4.1 Externalities of Deforestation Vary by Location of Source and Impact

Type of damage	Location of deforestation	Burden/location of impact
Global climate change	All deforesting locations; higher per hectare damages come from dense humid forests	Global
Imminent risk of globally significant biodiversity loss	Specific areas in mosaiclands and nonremote frontier forests	Global, but especially on high-income populations and future generations
Long-term risk of globally significant biodiversity loss	Frontier and transfrontier forests	Global, but especially on high-income populations and future generations
Local and regional climate change	Unclear, possibly widespread	Unclear, possibly widespread
Smoke and smog from forest fires	Most areas of rapid deforestation	Populated areas downwind of large, rapid deforestation
Local flooding, erosion, and diminished dry season flows	Small, steep upper watersheds in mosaiclands, nonremote frontier forests, and short littoral watersheds	Small, steep lower watersheds in mosaiclands; coral reefs
Reduced water quality for drinking and irrigation	Small, steep watersheds near cities and reservoirs	Downstream cities and reservoirs
Loss of pollination, pest control, and other biological services	Mosaiclands; high-density frontier forests	Fields near deforesting locations; possible far-field effects

from which cities draw their water, or along the erodible margins of rivers. Fine-tuning the behavior of a watershed requires attention not just to the presence or absence of trees but also to their placement, to agricultural activities, and especially to road placement and maintenance. Native trees will not necessarily be superior to agroforestry or other kinds of vegetation in achieving hydrological benefits. So biodiversity conservation may not be the best way to achieve hydrological benefits. On the other hand, forest conservation motivated primarily by biodiversity could pay dividends in hydrological benefits—perhaps even in large river basins.

Nonetheless, scientific understanding of hydrological processes is incomplete. Large-scale deforestation could affect regional climate in some circumstances. And the extent to which deforestation could lead to reduced dry-season flows is debated. More scientific and economic research is needed to pinpoint situations where deforestation poses these risks.

This is also true for other externalities in table 4.1. Because these externalities can be both subtle and important, solid demonstrations of their magnitude will be needed to motivate policy makers and their constituencies to take action to correct them.

Endnotes

1. This point is an adaptation of Hamilton and King's (1983) metaphor: "roots may be more appropriately labelled a pump rather than a sponge," quoted in Bruijnzeel (2004).

2. The map does not distinguish areas prone to shallow landslides, argued above to be most sensitive to loss of forest cover.

3. This term means that, in the absence of intervention, the habitat has a low to medium probability of surviving over the next 15 years. But the WWF classification does not necessarily imply the complete loss of trees, as the simulations assume.