Ecosystem Services from Tropical Forests: Review of Current Science

Katrina Brandon

Abstract

Tropical forests exert a more profound influence on weather patterns, freshwater, natural disasters, biodiversity, food, and human health – both in the countries where forests are found and in distant countries – than any other terrestrial biome. This report explains the variety of environmental services tropical forests provide and the science underlying how forests provide these services. Tropical deforestation and degradation have reduced the area covered by tropical forests from 12 percent to less than 5 percent of Earth's land area. Forest loss and degradation has reduced or halted the flows of a wide range of ecosystem goods and services, increasing the vulnerability of potentially billions of people to a variety of damaging impacts. Established and emerging science findings suggest that we have substantially underestimated the global importance of tropical forests and the impacts of their loss on human well-being.

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Ecosystem Services from Tropical Forests: Review of Current Science

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Foreword

This paper is one of more than 20 analyses being produced under CGD's Initiative on Tropical Forests for Climate and Development. The purpose of the Initiative is to help mobilize substantial additional finance from high-income countries to conserve tropical forests as a means of reducing carbon emissions, and thus slowing climate change.

The analyses will feed into a book entitled *Why Forests? Why Now? The Science, Economics, and Politics of Tropical Forests and Climate Change.* Co-authored by senior fellow Frances Seymour and research fellow Jonah Busch, the book will show that tropical forests are essential for both climate stability and sustainable development, that now is the time for action on tropical forests, and that payment-for-performance finance for reducing emissions from deforestation and forest degradation (REDD+) represents a course of action with great potential for success.

Commissioned background papers also support the activities of a working group convened by CGD and co-chaired by Nancy Birdsall and Pedro Pablo Kuczynski to identify practical ways to accelerate performance-based finance for tropical forests in the lead up to UNFCCC COP21 in Paris in 2015.

This paper, "Ecosystem Services from Tropical Forests: Review of Current Science" by Katrina Brandon, was commissioned by CGD to synthesize a vast scientific literature on the contributions that tropical forests make to fresh water provision, food security, energy, health, and human safety, collectively termed ecosystem services. The paper is intended to provide an up-to-date review of scientific understanding that is accessible to non-specialist readers.

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Executive Summary

Tropical forests once covered 12 percent of Earth's land area; now they cover less than 5 percent. Yet no other terrestrial biome exerts a more profound influence on weather patterns, freshwater, natural disasters, biodiversity, food, and human health – both in the countries where forests are found and in distant countries. Tropical deforestation and degradation reduce or halt the flows of ecosystem goods and services, while increasing the vulnerability of billions of people to damaging impacts. While we have known about the many benefits of forests and consequences of their loss for decades, recent findings show we have substantially underestimated both their global importance and the impacts of their loss.

The role of tropical forests in regulating global climate and weather patterns – especially rainfall and temperature – is of fundamental importance not only to poor rural farmers in the tropics, but to farmers and policymakers as distant from the tropics as the Midwestern United States and Texas, China and Mongolia, Canada, Siberia, northern Europe, and Scandinavia. Tropical forests return up to 90 percent of the rainfall they receive to the atmosphere, and winds passing through tropical forests produce twice the rainfall as winds passing across open lands. At regional scales, this makes forests vitally important to agriculture. Tropical deforestation affects local, regional, and even long-distance global climate (known as teleconnections), mostly by reducing the moisture and rainfall crossing oceans, making temperatures hotter and storms more intense. Eighteen global climate teleconnections are described, emphasizing the global relevance of tropical forest protection and health, especially given climate change.

Anyone concerned with freshwater – from hydropower plant operators to city water officials to agricultural ministries – should be interested in the role of tropical forests in rainfall, storing groundwater and providing clean water. For example, one Amazonian study showed that declines in forest cover were nearly equaled by declines in water supply – showing less forest equals less freshwater. Less forest also makes dry seasons last longer, while afforestation with native species can begin to reverse these effects. Upland forests and cloud forests are particularly important for economic sectors depending on water due to their role in water capture, storage and flows. Forests near rivers are also critically important for maintaining river health, vital to reducing sediments, ensuring productive fisheries, and reducing river temperatures. Since rivers often flow to lakes or the sea, reducing siltation is important for sectors concerned with everything from hydropower and fisheries to ports and coastal transport, and coastal tourism and fisheries.

Natural disaster mitigation is another service tropical forests provide – from reducing soil erosion and landslides to reducing the intensity, duration, and severity of floods. Tropical lands with slopes over 25 degrees are highly susceptible to surface erosion and landslides if they are deforested, and while trees and crops may be replanted there, they lack the characteristics of native forests to hold soils in place. Heavy storms, monsoons, and cyclones feature prominently in most tropical areas, and tropical forests buffer torrential rainfall, by absorbing water and returning moisture to the air, thereby reducing flooding frequency and duration. Coastal forests, especially mangroves, provide a huge protective function to coastal communities from storms, peak tides, and even small tsunami waves. The trees and their root systems break up the wind, and reduce wave energy and height. Healthy tropical forests rarely experience fire due to their high moisture, and when natural fires happen from lightning, they generally go out quickly. Yet fragmented and degraded forests have lower humidity, heightening the risks and impacts of tropical forest fires, which are increasing.

Tropical forests provide diverse ecosystem services largely because they have high density and diversity, packing in a lot of species and biomass compared to other forests. Tropical forests have incredibly high species diversity– and moist tropical forests contain over two-thirds of all land-based species. Higher biodiversity can be thought of as biological insurance – it provides some redundancy, which can be critical in supporting both ecosystem stability and resilience. Resilience is the ability of ecosystems to withstand, reorganize and rebound after a shock. Higher biodiversity also makes for a higher flow of ecosystem goods and services, because more possible pathways are used.

Food security is closely linked with tropical forests, both directly though forest foods (goods) but also through services such as pollination and pest control. About 70 percent of leading global crops, and over one-third of the global food supply, depend on wild pollinators, which are also especially important for many higher value crops, such as fruits and nuts. With a global decline in pollinators, specific crops are at risk – and many of these are tropical crops important to small farmers for food or countries for cash. Scattering seeds and controlling pests are also benefits that bats, birds and other tropical forests species provide for free. Wild foods from forests form an important safety net for rural families, and higher forest cover has been linked to better nutrition and health because people near forests eat forest foods, providing better diets and nutrition. Freshwater fisheries are rarely considered as part of forests – but the benefits tropical forests provide to river systems is huge in key tropical areas, such as the Amazon basin and Mekong River and delta. Coastal mangrove forests provide an extremely valuable set of ecosystem services—among these is serving as hatcheries for offshore fisheries.

Human health is closely linked to tropical forests – especially given the links between deforestation and emerging infectious diseases and pandemics. Deforestation brings changes in disease vectors; malaria incidence has often been found to be higher in areas where forests have recently been cleared. Diseases as broad as Ebola, yellow fever, and avian influenza have some link to deforestation. Traditional medicines, many from tropical forests, serve as many as 4 billion people. Of drugs approved to treat cancer, nearly half are derived from natural products. Deforestation, especially forest burning, is responsible for high emissions of particulates – threatening human health both near the fires, and at a distance, as particulates with copper and carcinogens travel across oceans.

Many economic sectors are affected by deforestation. The soil erosion that follows upland deforestation fills rivers with silt, reducing water quality to people, diminishing hydropower generation, and damaging infrastructure and homes, since it leads to faster and more devastating mudslides and flooding. River health is damaged, reducing fisheries and water quality and as rivers flow out to the sea, coastal fisheries and tourism are both damaged as silt harms fishing and reefs. Upland deforestation at broader scales reduces regional rainfall, affecting agriculture and hydropower installations, and even drinking water supplies.

All of these impacts from deforestation especially affect poor and economically marginal people, who often depend on nature's resources, and may be unable to afford substitutes for either products they directly consume (e.g. clean water, wild fish and meat) or services that benefit them (e.g. disease control or pollination). Deforestation also increases the vulnerability of all people, but especially poor people, to the many natural hazards that will increase with climate change.

Tropical forest degradation, loss, or conversion can significantly reduce or eliminate the flow of ecosystem services. Many human uses of forests can diminish forest health, and the higher flows of ecosystem services come from the healthiest forests. Degraded and fragmented forests, secondary forests, and plantation forests all have a lower variety and quality of ecosystem goods and services flowing from them compared to intact, healthy forests. Tropical forests are already showing signs of stress from climate change. Yet we know what some of the best practices are to maintain healthy tropical forests and insure ecosystem service delivery. Protection of large, healthy, stands of unbroken forest maintains the services these forests provide, as do actions to protect and connect remaining forest fragments. Economic development in tropical countries will be more equitable and sustainable if it is grounded in understanding, valuing and protecting tropical forests and their many services.

1. Introduction

The purpose of this report is to explain the **variety** of environmental services tropical forests provide and the science underlying **how** these services are provided. While there has been extensive, long-term research on tropical forests, there has been a recent shift to move beyond "basic" ecological research to understand forests, their functions, and services, within the context of an ecosystem services framework. The Millennium Ecosystem Assessment (2005) describes the concept of ecosystem services as "the benefits that people receive from nature." Since then, there have been many ways that economists have valued these benefits (Mullan forthcoming 2014). But the starting point for valuing benefits is figuring out how forests provide these benefits, and the conditions that shape the flows of these benefits to people.

This paper provides a brief synthesis of recent science on the ecosystem services provided by tropical forests beyond carbon storage. The intended audience is a non-technical one, and there are simplifications in the paper to make basic points and findings accessible to a non-technical audience. Both uncertainty and debate are prevalent in discussions on forests, which is a natural part of the process of science, as each year brings new understanding and findings. What is remarkable is the tremendously fast pace of learning that is underway, as our understanding of the value of tropical forests has increased, along with threats to forests and their loss. Scientists from a wide range of disciplines are engaged in a process of dynamic learning to understand the incredibly complex relationships that exist in different tropical forests. This research is all taking place in often challenging field conditions, with sporadic research funding, while forests themselves may already be under stress from human actions – including climate change.

The paper first introduces the value of tropical forests through several striking cases from around the world. The paper then provides a primer on the tropical forests' geography, structure, basic processes and health of tropical forests (Section 2). Shaded text boxes highlight key information. Sections that follow look at the role of forests in global weather patterns, including the connections across distant places, and their influence on rainfall and temperature (Section 3). The role of forests in freshwater quality and availability, and coastal forests, is then described (Section 4), followed by a discussion of forests and natural hazards (Section 5) such as landslides, flooding, coastal storm waves and tsunamis, and fire resistance. The importance of biodiversity (Section 6) and the links to food (Section 7) through pollination and pests, wild foods, and freshwater fisheries, are discussed – recognizing that the nutritional benefits described here have an important influence on human health (Section 8), and the ways that forests prevent diseases, and provide medicines. The conclusion briefly highlights the key elements needed to protect tropical forests into the future.

A. Losing Forests, Diminishing Development, and Increasing Poverty

Haiti provides a clear example of how destroying the country's forests led to the collapse of agriculture, freshwater, reef systems, leading to enduring poverty, damaging infrastructure and increasing the impacts of natural hazards. Haiti and the Dominican Republic share the island of Hispaniola, which was once covered by abundant forests. Satellite images of the border show the sharp contrast between Haiti's denuded landscape (on left) and the Dominican Republic's remaining forests (on right, Figure 1).[1] Many of Hispaniola's moist lowland forests were cleared centuries ago for plantation agriculture when the island was colonized by the French and Spanish, with forest clearing accelerating in the twentieth century. In the 1920's, 75 percent of the Dominican Republic was forested, dropping to 40 percent by 2010 (Brothers 1997; FAO 2010). In Haiti, the 90 percent Pre-Columbian forest cover dropped to 60 percent by the 1920s, and a shockingly low 4 percent in 2010 (FAO 2010; Williams 2011).

[1] Recent estimates of tree cover by Hansen and coauthors (2013) suggest that there could be more tree cover (up to 32%) in Haiti than previously thought, but if this new data is correct, it measures many small, fragmented patches of trees rather than forests. They also estimate tree cover in Dominican Republic at 51 percent (Hansen et al. 2013). Also see Churches et al. (2014).

Figure 1: Haitian-Dominican Republic Border between Sylvestre and Restauracion, February 2011

Source: Image by DigitalGlobe, obtained via Google Earth

Many of Haiti's problems can be traced to deforestation. While eastern winds delivered more moisture to the Dominican Republic side, the upland forests helped regulate the uneven patterns of rainfall, making the Haitian side productive for farming. Without the forests, Haiti has become increasingly dry and desertified (Williams 2011). Topsoil has eroded and washed away from productive lands, and about 40 percent of the country's land area has degraded soils (Bai et al. 2008). One Haitian writer, returning to the village where he had grown up recounted the devastation wrought on the landscape and its people during his lifetime:

> *"When I visited my village…, it was all brown. No vegetation. Most of the trees I used to see as a boy had been cut down. The birds had left the village. No place to build their nests or for them to rest. No rainfall. The rivers were almost all dried out. My neighbors had moved to other areas… My village is like a desert…" (Vedrine 2002).*

Deforestation has also caused the country's waterways to become badly silted. Authorities have resorted to piling sand on the road connecting Port-au-Prince to the lakeside town of Malpasse to counteract the rising waters, as the original road is more than two feet below the surface already (Gronewold 2009). Bare slopes in the largely mountainous country have become increasingly exposed to landslides and flooding after heavy rains during the rainy season (Than 2010). "Just one day of continuous rain is devastating, it can cause catastrophe," describes Haiti's Minister of Environment, Jean François Thomas (Lall 2013).

The few forests left are both critical for local wood and charcoal in the absence of other energy supplies, but are dwindling, and farming is becoming increasingly untenable, leading to migration from the countryside to city slums (Alscher 2011). Deforestation also extends to Haiti's coastal mangrove forests, which are disappearing at an alarming rate, declining in area by 28 percent between 1980 and 2005 (Gingembre 2012).[2] Mangrove loss affects a broad range of economic sectors, limiting fisheries, reducing water quality, and increasing the risks of natural hazards.

In 2013, Haiti's government finally recognized that forest restoration is essential to the country's long-term development, announcing an ambitious tree-planting initiative to double the country's forest cover (Lall 2013). Yet there have been numerous reforestation projects supported by international donors and NGO's over the past 30 years that have had only muted success given the high costs and complex challenges in restoring badly degraded habitat, stemming the drivers of deforestation, and managing and protecting what is left, and many are skeptical of government's ability to achieve this reforestation goal (Williams 2011; Lall 2013). The nexus of deforestation and its cascading effect on other sectors, entrenched poverty, and political instability in Haiti are in contrast to the context in the neighboring Dominican Republic. While the two countries were shaped by very different colonial legacies, they illustrate the dramatic differences of outcomes that are linked to forest use and management (Alscher 2011). The Dominican Republic retains about 37 percent in forests, and ranks 75 of 178 countries on the Environmental Performance Index compared to Haiti's rank of 176 (EPI 2014).

Another illustration of the value of tropical forests can be found on the other side of the world, in the Indian coastal state of Odisha[3] in the Bay of Bengal, which has frequent tropical cyclones. Odisha directly witnessed the important role of effectively managed mangrove forests in reducing the loss of life, property, and infrastructure from storms. The October 1999 super cyclone that struck Odisha killed nearly 10,000 people and caused more than $5 billion in property damage. Villages where seaward mangrove forests had been conserved had fewer deaths versus areas where mangroves had been removed, even after accounting for a slew of confounding factors (Das and Vincent 2009; Das 2011). Mangroves attenuated the destructive force of the cyclone, slowing waves and floodwaters in their complex root structures and along their muddy bottom surface. They also reduced

[2] The rate of mangrove destruction in Haiti is comparable to that in other countries in the tropics. Globally, the FAO reports that 20 percent of mangroves were lost between 1980 and 2005 (FAO 2007).

[3] Called Orissa until 2011.

maximum wind speeds on their leeward sides (Das and Crépin 2013). Property losses in villages sheltered by mangroves were lower than in villages without forests or with only embankments. The mangroves also allowed floodwaters to drain back to the sea, while villages with only embankments saw fields flooded for longer and crop production was more severely affected by the brackish water. Interviewed after the storm, most local village residents said they thought the mangroves were beneficial to their lives and property, with nearly 90 percent citing flood control and reduced damages from the cyclone as the primary benefit (Badola and Hussain 2005).

Honduras also illustrates the links between deforestation, natural disasters and poverty. Between 1990 and 2005, Honduras lost 37 percent of its forest cover--about 2.74 million hectares. Before Hurricane Mitch struck Central America in 1998, Honduras was steadily reducing poverty. But Mitch caused $2.2 billion in direct damage to property, or $3.8 billion for all losses (IADB 2000). Subsequent discussions highlighted how high rates of forest clearing combined with Mitch turned a hazard into a disaster. Despite the massive investment in Honduras after Mitch, deforestation increased by nearly 9 percent -- this means that the conditions that will trigger future destruction worsened, increasing the potential impacts of smaller hurricanes than Mitch.

With continued warming over the next century, it is likely that tropical cyclones such as Mitch will become more violent, with higher wind speeds and rainfall rates. The frequency of the most severe storms may also increase (Seneviratne et al. 2012). The inland impacts are particularly troubling for Haiti, Honduras, the Philippines and many other tropical countries, where the nexus of poverty, deforested and eroded slopes, and high runoff exist. Upland deforestation is particularly concerning, leading to soil erosion and faster water runoff, exacerbating downstream infrastructure destruction and flooding.

B. Increasing Understanding of Tropical Forest Ecosystem Services

With tropical deforestation responsible for 10.3 billion tons CO_2 equivalent of global greenhouse gas emissions each year—about twice the total GHG emissions for the United States (IPCC 2013)— policy recognition of the carbon storage benefits of tropical forests, in particular, has grown quickly in the international area. Momentum is building to include reducing emissions from deforestation and forest degradation as well as conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD+) in a climate change agreement. Most recently, the 19th Session of the Conference of the Parties to the UN Framework Convention on Climate Change (COP19), held in Warsaw in November 2013, solidified a framework agreement on possible sources of results-based financing; transparency and safeguards; technical issues with measuring, reporting, and verifying emissions from forests; and institutional arrangements for REDD+ (La Vina and de Leon forthcoming 2014).

As policy recognition of the carbon storage benefits of tropical forests builds, funding has increased. Nearly $9 billion in financing for forests was mobilized in 2012 (Norman and Nakhooda 2014). Funding for REDD+ activities has come from a variety of multilateral institutions and financing mechanisms. The Forest Carbon Partnership Facility, a partnership of governments, businesses, civil society, and indigenous peoples, has raised $825 million to support countries in REDD+ readiness activities and pilot projects in 44 developing countries in Africa, Latin America and the Caribbean, and the Asia-Pacific region.[4] The Forest Investment Program, a REDD+ program in the Climate Investment Funds framework managed by the World Bank, has raised $639 million in pledges for activities in eight tropical forest countries (Norman and Nakhooda 2014).[5] The UN-REDD Programme—a joint initiative of the United Nations Environment Programme (UNEP), the UN Food and Agriculture Organization (FAO), and the UN Development Programme (UNDP)—has provided $187 million for REDD+ activities.[6] Additional, limited investment in REDD+ has come from private sources, including over $210 million annually from the sale of verified emission reduction credits in voluntary carbon markets (Norman and Nakhooda forthcoming 2014; Henderson et al. 2014). In reality, the financing deployed for REDD+ so far is a small percentage of what will be needed to effectively curb the loss of tropical forests. By some estimates, between $15-33 billion in funding is needed annually to halve deforestation by 2030 (Lowery, Tepper, and Edwards 2014).

Beyond carbon storage, international conventions have recognized the other multiple benefits provided by forests. The Convention on Biological Diversity (CBD), adopted by 194 countries, for example, has enshrined the importance of forests for the world's biodiversity and the flow of ecological services. Forests are vital to the strategic goal of halting biodiversity loss by 2020, set forth by the parties in Nagoya, Japan in 2010.

[4] Forest Carbon Partnership Facility, "About FCPF," https://www.forestcarbonpartnership.org/about-fcpf-0.

[5] The countries are Brazil, Burkina Faso, Democratic Republic of Congo, Ghana, Indonesia, Lao PDR, Mexico, and Peru. Climate Investment Funds, Forest Investment Program, https://www.climateinvestmentfunds.org/cif/node/5.

[6] UNDP, Multi-Partner Trust Fund Office Gateway, "UN-REDD Programme Fund," http://mptf.undp.org/factsheet/fund/CCF00.

Important forest-related targets in the CBD's strategic plan include halving the loss of natural habits, ensuring that all areas under forestry are managed sustainably, and expanding protected areas to 17 percent of the world's land area.[7] The Convention on Combating Desertification, likewise, recognizes the important role that protecting forests plays for preventing the spread of deserts and drought.

A prerequisite for mobilizing additional political support and financing for tropical forests is improving scientific knowledge and measurement of the many economic benefits that flow from forests (Mullan forthcoming 2014). Taking steps in this direction, some tropical countries are moving toward valuing their forest assets as part of their national accounts to assist in policymaking. Countries that have developed or are in the process of developing forest accounts include Brazil, Chile, Colombia, Costa Rica, Indonesia, Madagascar, Mexico, Philippines, South Africa, Swaziland, and Thailand (WAVES 2014).[8] Statistical guidelines for creating forest accounts have been approved by the UN as part of the System of Environmental-Economic Accounting (SEEA) (UN-EU-FAO-IMF-OECD-World Bank 2014). The best evidence that tropical countries are recognizing the real value of forests to their long-term economic development and wellbeing may well be the use of these forest ecosystem accounts and their integration into policymaking.

[7] CBD, COP 10 Decision X/2, http://www.cbd.int/decision/cop/?id=12268.

[8] These include countries of the Wealth Accounting and the Valuation of Ecosystem Services (WAVES) partnership. WAVES, Partners, http://www.wavespartnership.org/en/partners.

2. Understanding Tropical Forests

Tropical forests:

- covered 12% of the Earth's land area originally but now cover less than 5%.
- exist only between the Tropics of Cancer and Capricorn.
- span a range of forest types, from tropical rainforests to moist forests, dry forests, to montane cloud forests and mangroves, and each type of provides a different suite of ecosystem services.
- provide ecosystem services worth twice the value of temperate forests.
- have a high diversity and number of trees and plants species with different heights, giving them many layers, a high surface area, and high biomass in a small area.
- slow, capture and recycle fog and rain and directly pump humidity back into the air which prevents erosion and flooding.
- are the most biodiverse systems on Earth, and this high biodiversity supports resilience – the ability of ecosystems to withstand shocks.

Tropical forests historically occupied about 12 percent of the Earth's land area, but today make up less than 5 percent (600 million ha.) of the Earth's terrestrial surface—or about 28 percent of land in the tropics (Corlett and Primack 2011; Hansen et al. 2013). They are only found between the Tropics of Capricorn and Cancer. Where rainforests were once found in large unbroken blocks, few such blocks remain, with the Amazon Basin, Indonesia, and the Congo Basin holding the last large areas. The remaining tropical forests are not all the same – there are several types, and the broad categories of tropical forests are presented in table [1] and their geographic distribution illustrated in figure [2]. Different types of tropical forests have different levels of biodiversity and provide different levels and types of ecosystem services. Tropical rainforests are the most biodiverse and productive forests, with net primary production (incremental wood growth plus leaf litterfall) averaging around 22 tons of biomass per ha per year, compared to 13 tons per ha per year for temperate evergreen forests (Montagnini and Jordan 2005: 42). To illustrate the differences in ecosystem services provided by two types of forests, researchers have compared the ecosystem services of tropical forests of $2,355 to $1,127 for temperate forests (looking at average annual value per hectare) (Costanza et al. 2014).

Figure 2: Tropical Forest Biomes

Source: author; data from FAO, UNEP, and WCMC

Table 1: Tropical Forest Classifications, by Ecological Zone

	RAINFOREST	MOIST FOREST	DRY FOREST	MONTANE FOREST	MANGROVES
CLIMATE	High temperatures and heavy annual precipitation (at least 1,500 mm, but often 2,000-3,000 mm), with a short (3 months) or absent dry season.	Tropical climate with summer rain and a 3 to 5 month dry period. Yearly rainfall ranges of 1,000 to 2,000 mm.	Tropical climate, with summer rains and a 5 to 8 month dry period. Annual rainfall ranges from 500 to 1,500 mm.	High variety of climatic conditions, varying with altitude (between 1,000m and about 4,000m)	Coastal
VEGETATION	Evergreen and semi-evergreen forest, with lush vegetation, tall, closely set trees forming a continuous multi-layered canopy and emergent trees reaching 50 to 60 meters high. Most diverse terrestrial ecosystem, with a large number of tree species.	Semi-deciduous and deciduous forests, such as monsoon forest (Asia), cerrado (South America), and wet Miombo woodlands (Africa).	Dry tropical forest and woodland, including drier type of Miombo and Sudanian woodlands, savana (Africa), caatinga and chaco (South America), dry deciduous dipterocarp forest and woodlands (Asia).	High variety of vegetation types along altitudinal belts, ranging from evergreen submontane rainforest to cloud forest, with shorter tree height as altitude increases. Treeline typically located around 4,000m above sea level, though varies.	Trees and shrubs that live in brackish, tidally flooded soils along coastlines and estuaries, typically with a simple structure and low plant diversity, though mangroves provide habitat for a unique array of marine, estuarine, and terrestrial species

Source: FAO (2001) and Thompson et al (2012), with some modifications

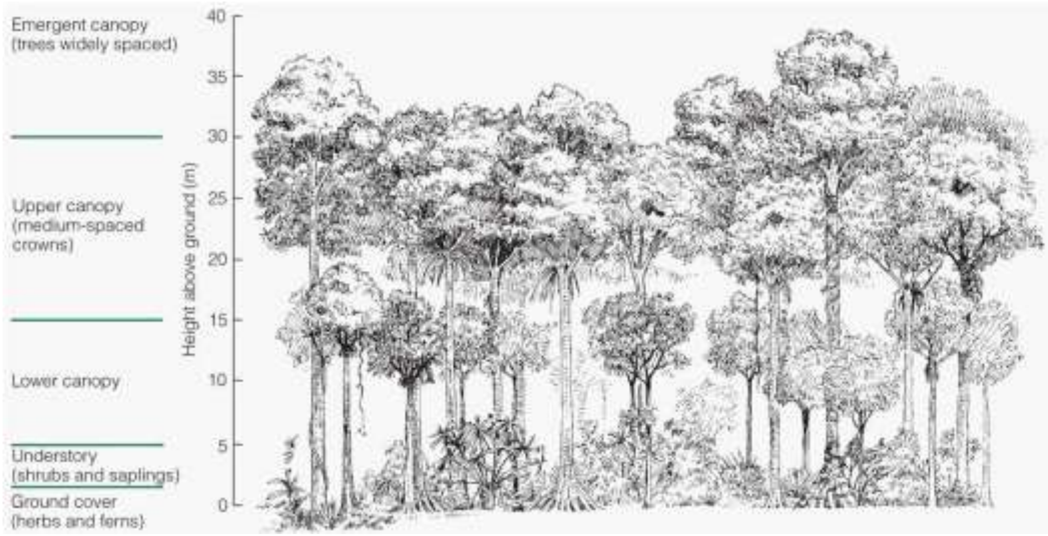
Tropical forests provide this variety of ecosystem services as a result of many factors related to ecosystem structure and functioning (such as climate, topography, geology (e.g., soil types), resource availability (e.g., water and nutrients), disturbances (e.g., fires), biotic communities (e.g., diverse groups of species), and human activities (Chapin, Matson, and Vitousek 2011). Factors that make tropical rainforests unique include their closeness to the equator, which affects light availability and growing season; moisture; temperature; and the richness of species. Biodiversity generally enhances ecosystem functioning, although the relationship between the supply of specific ecosystem services and biodiversity is not entirely clear (Elmqvist et al 2010). Some services, such as pollination and biological pest control are closely linked to biodiversity. Others, such as fresh water supply and water purification, depend more on healthy and intact forests at the landscape or regional scale than on characteristics such as species diversity (Thompson et al 2012). The supply of ecosystem services also varies among primary, secondary, and plantation forests. Primary forests are relatively unused forests, where any substantial human intervention has happened in the distant past. Secondary forest has regrown after being cleared or badly disturbed (e.g., by a fire or insect infestation). A plantation forest is a cultivated forest, often characterized by a single tree species planted in regularly spaced stands.

A. The Structure of Tropical Forests

The structure of tropical forests is quite different from other forests (e.g. temperate) and ecosystems (e.g. grasslands). Understanding this is essential to understanding how forests deliver services, how tropical forests differ from other types of forests and how climate change will affect them and the level of services they provide. Key factors that contribute to the unique structure of tropical forests are their warm temperatures, constant sunlight throughout the year, high precipitation, and high biodiversity. Additionally, and critical to ecosystem services is their many layered and dense structure, which affects everything from biodiversity to regulating water flow (figure 3).[9]

[9] The following discussion focuses mainly on moist forests and rainforests.

Figure 3: Layering in Tropical Rainforests



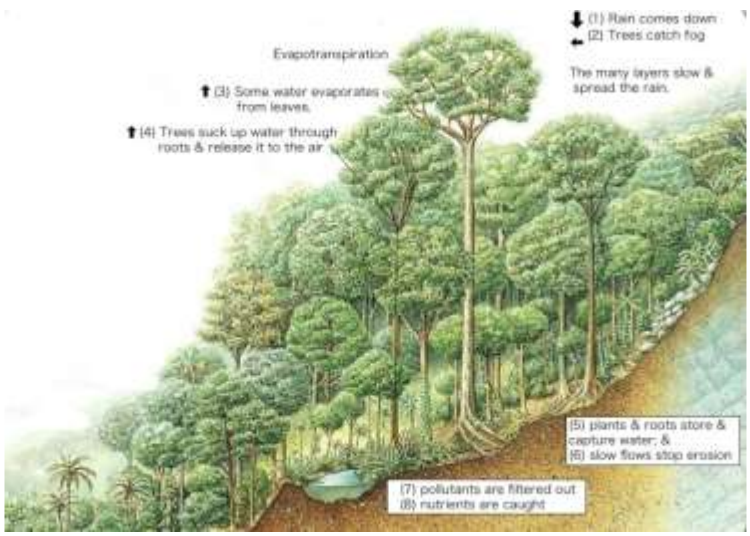
Source: Pearson Education, Inc.

The huge number of leaves at different levels buffers the impact of hard intense tropical rainfall, acting like many umbrellas stacked at different heights catching, softening, channeling, and distributing the water flow. Tropical soils are typically shallow and poor quality. Yet the diversity of plant life, including different trees, shrubs, vines, and even mosses help anchor the soils at different levels, and the litter layer also protects the soil from harmful impacts of rain. Underground, the root systems store carbon, and large roots form the equivalent of nets, holding the soil in place, even on slopes.

High biodiversity is related to the many habitats, food, and opportunities (the ecological niche) for different species result from this layering. Another characteristic of layering is the high surface area and large amount of biomass in a compact space, which is critical to the role of forests in the water cycle and climate.

Imagine a typical rainstorm in the humid tropics that drops a huge amount of water onto a healthy, hillside forest. Hours later, the sun is out, the air is warm and muggy, and the water has seemingly disappeared. Now imagine an adjacent largely deforested hillside with pastures and subsistence crops. By the next day, it is clear that the storm directly damaged crops, and the rapid runoff has created deep gullies and mudslides, and flooded fields. The rushing water moves downstream, carrying with it all kinds of debris, which destroys bridges connecting remote villages to market towns. Further down, the silt becomes evident, damaging hydroelectric equipment for the nearest city. Days later and hundreds of miles away, silt and debris flow out of a river settling onto offshore coral reefs and decimating the fishing grounds of coastal fisherfolk. Figure 4 explains what happens in a forest when it rains, and how tropical forests differ from other ecosystems, or from agricultural settings, and numbers in the text correspond to the figure.

Figure 4: Tropical Forests: What Happens When it Rains



Source: adapted from Acreman et al. 2012

Catching what comes down: Rain (1) and Fog (2) are intercepted by trees. When the torrent of rain first hits the top and outer leaves of the forest, the multitude of leaves and branches reduces the impact of the rain on any one place, and catch and spread and channel the water.

Moisture goes back up: Evapotranspiration (ET) is the total amount of moisture returning to the sky, made up of the moisture that stays on leaves and branches and that directly evaporates (3) and the water that drops to the ground and is sucked up by the roots of trees and plants, and then travels up to the leaves and released into the air (4) through the process of transpiration. More leaves equal higher transpiration.

Water captured underground: Forests are especially good at catching and storing water (5) underground, such as along root systems, or in pockets left by bugs and animals, and providing greater potential for it to seep into the ground (infiltration) and go to aquifers instead of flowing overland.

Slowing flows: Strong rainfall impact is reduced and spread out (over area and time) by the many layers of vegetation, which also form a series of obstacles, reducing water flow and soil erosion (6).

Cleaning and greening: The high diversity of plants and animals clean water and remove pollutants (7) as water slowly filters underground to aquifers or catchments.

Recycling nutrients: Nutrients that are (8) washed from higher ground are captured and reused by other vegetation down slope or nearby. Tree litter decomposes and is held in place by vegetation and roots in the understory.

Influencing weather: How water is captured and then released by individual plants and trees is magnified by forests. Patterns of rainfall and evapotranspiration have been linked to broader scale atmospheric processes, such as winds.

B. Tropical Forests and Biodiversity

The high diversity of trees and plants creates a layering effect in tropical forests, and the variation in conditions across rainforests (e.g. altitude rainfall, soils), create many different ecological niches – and tropical rainforests have a huge diversity of species that have evolved to take advantage of these opportunities. Tropical forests contain the highest biodiversity found on land. A single tree in the Peruvian Amazon may be home to more ant species than the entire British Isles, for example, and more tree species can be found in less than one square kilometer of tropical rainforest in Malaysia than in all of the United States and Canada (cited in Montagnini and Jordan 2005: 10).

In understanding forests, scientists look at the different groups of organisms that provide different ecological services, such as dispersing seeds, pollinating plants, acting as predators, fixing nitrogen, decomposing wastes, and other functions. The variety of different tree species adds to forest complexity, with very different heights, root systems, transpiration rates, chemicals in the bark and leaves, flowering and fruiting, which in turn affect their relationships with animals – who eats and disperses their seeds, who lives in them, who tries to eat them. Seeds are widely dispersed through an array of mechanisms. They may have wings to help them catch the wind, they may be explosively popped from pods, or they can hitchhike on or in mammals and birds. Decomposition of waste matter is another basic process, provided first by insects and then by many smaller organisms. This huge diversity matters because it is closely related to tropical forest health and the capacity of forests to deliver ecosystem services, as we will see in later sections.

3. Forest, Weather, and Climate

Tropical forests:

- provide 33% of the world's terrestrial net primary production (NPP) and store about 25% of terrestrial carbon (even though they are less than 5% of the Earth's land surface).
- capture the sun's energy and return it to the atmosphere through high evapotranspiration (ET) and they are the most efficient ecosystem at returning moisture to the air, which increases cloud formation and reflects heat, reducing warming.
- drive local, regional, and global climate cycles and weather – creating rain, winds, and shaping weather patterns by cycling of heat and releasing moisture (ET).
- create teleconnections, which affect long-distance weather patterns, so losses of Brazilian rainforest can lead to midwestern USA drought or make southern Europe cooler.

The Earth's climate is determined by the flows of energy and materials between the atmosphere, oceans, and terrestrial systems. Energy flows are made up of radiation and heat, while materials include water, carbon, nitrogen, trace gases, and aerosols. The planet's ecosystems, both natural and human-dominated, generate both energy and materials, with different ecosystem types generating different balances of each. These in turn influence and regulate temperature, humidity, cloud cover, circulation, and precipitation over land and sea. Taken together, these affect atmospheric circulation patterns and climate, but their effects are what we notice on a daily basis as "weather." This set of ecosystem services provided by natural systems is called climate regulation, affecting atmospheric warming and cooling, water recycling, wind formation and patterns, cleaning atmospheric pollutants, and redistributing nutrients. These regulating properties range from localized rainfall patterns, to regional, sub-continental and global-scale flows. They also include the ability of ecosystems to mediate climate through other cycles, such as storing carbon (Díaz, Tilman, and Fargione, 2005).

Tropical forests are critical to local, regional, and global climate cycles principally through the moisture and energy that they return to atmosphere and the carbon they store. They account for about 25 percent of stored terrestrial carbon, and about 33 percent of the world's terrestrial net primary production (NPP), even though they make up less than 5 percent of global land area (Union of Concerned Scientists 2011). Emerging evidence suggests that forests, especially tropical forests, may drive global atmospheric conditions much more than previously thought (Sheil and Murdiyarso 2009; Sheil 2014). A recent and dramatic revision suggests that 80–90 percent of all atmospheric moisture passes directly through plants (transpiration), rather than the 20–65 percent as previously thought (Jasechko et al. in Sheil 2014).

Different types of ecosystems influence climate and weather differently, depending on their structure—evident if you contrast a grassland or tropical forest and consider their vegetation and biodiversity. Factors such as the height of plants, the density of vegetation, or even the arrangement of leaves can influence how much heat is absorbed or reflected back (affecting temperature), how much moisture is captured and released (affecting rainfall and temperature), or how high trees reach (affecting air movement) (Díaz, Tilman, and Fargione, 2005). About half of the Sun's energy reaching Earth is captured by vaporizing water, which helps with cooling, both locally and at broader scales. More trees vaporize more water, which leads to cooler temperatures.

Tropical forests are especially good at capturing the sun's energy and returning it to the atmosphere through high levels of evapotranspiration (ET), increasing both global moisture levels, and the moisture levels of downwind ecosystems (Shukla et al. 1990). Tropical forests exert a strong influence over the "service" of water recycling given the tremendous flows of water that they release into the atmosphere and are the most efficient ecosystem for these transfers for a number of reasons. First, their high layering and density, and deep root systems offer high opportunities for water capture and transfer. A review of 138 different types of tropical forests found that 30 percent to 90 percent of the annual rainfall to these forests was returned to the atmosphere as moisture (Kume et al. 2011) with annual evaporation exceeding 2 meters for some forests (Loescher et al. 2005; Baldocchi and Ryu 2011). In contrast, evergreen and deciduous oak woodlands cycle less than 0.5 meters per year, with boreal forests returning little moisture on a daily basis and only seasonally, when they aren't dormant. In contrast to temperate forests, tropical trees engage in photosynthesis daily, resting at night instead of during winter months. They therefore convert solar energy and rainfall into moisture that they pump back into the atmosphere on a year-round basis. This moisture increases the cloud cover, which in tropical areas reflects the sun's energy (known as albedo), helping broader scale cooling (Boysen et al 2014).

The structure of tropical forests, with many trees and trees of varying heights, increases the exchange[10] between the forest's water (ET), heat, and CO2 with the atmosphere. In a mature, old growth rainforest, the upper two-thirds of the tree canopy is coupled to atmospheric changes—such as wind, humidity, and light (Seidler et al. 2013). Even a low density of trees (e.g., less than 100 trees per ha) in a savannah system, for example, increases atmospheric exchanges. So tropical forests having greater atmospheric exchanges, thus influencing climate more than other ecosystems, given their high number of trees (Thompson et al. 2004).

Ecosystems are both sources and sinks of greenhouse gases and aerosols (very small atmospheric particles or droplets of biological or mineral origin) (Ellison, N. Futter, and Bishop 2012). An emerging body of science indicates that the particles emitted by tropical forests – such as pollens, bacteria and spores – may serve an important role in condensation and cloud formation (Sheil 2014), with highly productive ecosystems emitting more particles, thus making it easier for droplets to form and rain to fall. A recent study tracking tropical wind and rainfall found that winds passing forests produced twice the rain as wind passing over open land (Spracklen 2012).

A. Teleconnections: Lost There, Felt Here

Tropical forests influence the climate not only at local scales, but also in distant areas linked by atmospheric pathways called teleconnections. There is an emerging scientific consensus that these teleconnections link changes (e.g., deforestation) affecting climate and weather in one part of the world to other areas large distances away via changing atmospheric circulation and pressure patterns. The links between warm oceans and atmospheric patterns caused by El Niño events that lead to extreme weather events worldwide is one example of such teleconnections (Cai et al. 2014).

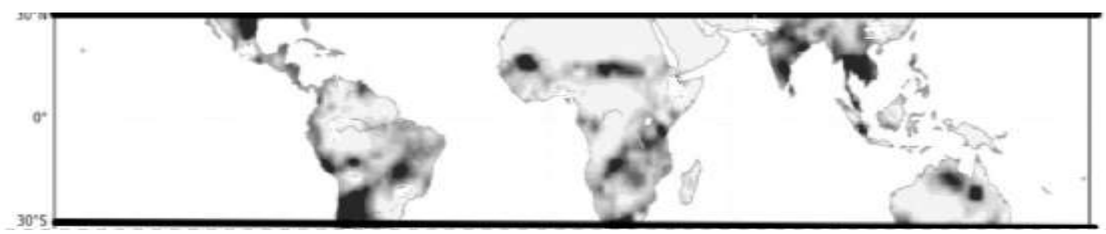
Tropical forest loss increases temperature and reduces rainfall (see figure 5), both locally and regionally, and in many cases, globally (Pielke et al. 2011; Mahmood et al. 2014). The Amazon, for example, is a major convection center that feeds the Hadley and Walker atmospheric circulations, which distribute thermal energy from the tropics and drive seasonal weather patterns such as the Pacific monsoons. Studies that have modeled the large-scale deforestation of the Amazon predict that the region would become hotter, drier, and less cloudy. By influencing global atmospheric circulations, the widespread loss of the

[10] Known as mechanical turbulence

Amazon forest would also redirect storm tracks in the North Atlantic and Europe, substantially cooling the climate of southern Europe and warming the climate of parts of Asia in the winters (Foley et al. 2007).

Land Use-Land Cover Change (LULCC) has reduced global evapotranspiration, reducing rainfall and increasing temperatures. Figure 5 shows the change in ET from pre-industrial times to the present, and the darker the area, the greater the decline in ET (Boisier, de Noblet-Ducoudré, and Ciais 2014).

Figure 5: Loss of mean annual evapotranspiration in the tropics from land use and land cover change



Source: adapted from Boisier et al. 2014 (darker areas show greater loss of ET)

Multiple analyses reveal that global, regional, and localized declines in ET are linked to deforestation, although the levels may vary. For example, Pires and Costa (2013) modeled what happens to precipitation with different levels of Brazilian deforestation. They found that even low deforestation could lead to a rapid drop in regional rainfall, suggesting, "at least 90 percent of Amazonia and 40 percent of Cerrado should be sustained to avoid subregional bioclimatic savannization." Similarly, global modeling showed a significant relationship between increased forest cover and increased precipitation, and lower temperatures (Osborne et al. 2004; Ellison, Futter, and Bishop 2012).

Locally and regionally, deforestation results in higher temperatures and reduced rainfall, but has other strong impacts through teleconnections. Current knowledge and conventional views on the impacts of LULCC on climate demonstrate clear and direct climate impacts (Table 2).

Table 2: Climate Teleconnections – Forest Cover Change and Climate Impacts*

ASIA	AFRICA	LATIN AMERICA
Evidence of deforestation decreasing Rainfall		
Worldwide: Even relatively localized clearing (especially coastal) can switch rainfall patterns at continental scales – reducing rainfall by 95 percent and changing the entire climate of continents from wet to arid[19].		
Complete Asian deforestation decreases rainfall: in Southeast Asia 1mm/day[1] 20-30 percent in southern China and Vietnam[2] 20-25 percent decrease in rainfall in western Turkey[3]	Complete African deforestation local widespread reductions in rainfall of 1mm/day[7] 2-3mm/day decrease in the dry seasonin Mozambique[8] Central African forest loss would decrease rain in US Midwest, by 5-35 percent[3]	Amazonian deforestation decreases rainfall 10 percent-20 percent across the Amazon basin[11] by 25 percent in Texas[3] up to 2mm/day drier in Northwest Amazon basin[13] Given current Amazonian deforestation trends[17]: 12 percent less in wet season 21 percent less in dry season 4 percent less in Rio de la Plata
Evidence of deforestation increasing rainfall		
	Complete African deforestation To Botswana, Zambia and the southern Democratic Republic of Congo[8] Central African forest loss increases Arabian Peninsula rainfall by 15 percent-30 percent[3]	Amazonian forest loss increases rainfall in Northern Europe[12] to the Arabian Peninsula rainfall by 45 percent[3] Afforestation in southern South America Increased rainfall by up to 0.5 mm day in spring and 1.0mm day in summer[14]
Evidence of deforestation increasing temperatures		
Worldwide: urban areas that replaced tropical forests are 6.5-9.0 C warmer[15]		
Complete Asian deforestation raises temperatures across the Asian region by 1°C[4] in Canada and central Africa [4]	South Sudan deforestation increases local temperature 1.2-2.4°C [10]	Converting the Amazon to agriculture increases regional temperature by 2°C[12]
Evidence of deforestation decreasing temperature		
Worldwide: afforestation and reforestation decrease near-surface temperature[16]		
Complete Asian deforestation makes Siberia of 1°C[4] colder		
Evidence of deforestation changing storm tracks		
Worldwide: current trends suggest a doubling in the frequency of El Niño events, disrupting weather patterns and bringing increased tropical cyclones, drought, fires, and floods [18]		
Complete Asian deforestation Increases storms over Scandinavia[5] Changes European storm tracks[5] Weakens the East Asian monsoon flow over eastern[2,6] China and the South China Sea, Increases the monsoon flow over mainland Southeast Asia[2,6]	West African deforestation weakens monsoon[9]	Amazonian forest loss triples the frequency of extreme cold events in the south and west of South America[13]
Evidence of deforestation changing ocean temperatures and affecting ocean circulation		
Complete Asian deforestation Makes the Southern and South Indian Oceans surface temperature up to 1.25°C colder[4] Warms the South Pacific Ocean by 0.75°C [4]		

Source: adapted from Miller and Cotter, 2013 with revisions and additions
1-Werth & Avissar, 2005a; 2-Sen et al., 2010; 3-Avissar & Werth, 2005; 4-Schneck & Mosbrugger, 2011; 5-Snyder, 2010; 6-Sen et al., 2004; 7-Werth & Avissar, 2005b; 8-Semazzi & Song, 2001; 9-Abiodun *et al.*, 2008; 10: Salih *et al.*, 2012; 11-Moore et al., 2007; 12-Feddema *et al.*, 2005; 13-Medvigy *et al.*, 2012; 14- Beltran-Przekurat *et al.* (2012); 15-Imhoff *et al.*, 2010; 16-Mahmood et al. 2014; 17-Spracklen et al. 2012; 18- Cai et al. 2014.

Studies combining LULCC with the emerging science of teleconnections make it clear that deforestation in one area leads to unexpected and distant problems in rainfall, temperature, and storm tracks. For example, rainfall to the US Midwest could decline by up to 35 percent if Central African forests are cleared (Werth and Avissar 2005).

Forests and Rainfall: Emerging Theories

A new theory, known as the "biotic pump" was introduced in 2007 (see Sheil and Murdiyarso 2009 for an explanation of Makarieva and Gorshov's biotic pump theory). The idea is that forests work like a giant pump, attracting and pulling moisture from oceans into the interior of continents, where it turns into rain. This theory explains why inland areas distant from oceans (think the interior of the Amazon or Congo basins) maintain high humidity and rainfall. Essentially moisture flows from coastal to inland forests, dropping rain with atmospheric currents cycling the dry air back to the ocean. The biotic pump theory predicts that even localized forest clearing can reduce or break coastal to inland moisture flows. While rebuffed initially (Gorshkov and Makarieva 2007), some recent analyses support this view, which explains how deforestation has shifted rainfall over southeast Asia (Tokinaga et al. 2012) and in the Amazon basin (Coe et al. 2013). However, this theory remains vigorously debated, and its validation (or rejection) will be a lengthy process.

The bottom line message is that tropical forests are especially important in shaping climate, rainfall and weather – at all scales, but most significantly at local and regional scales, although there are connections to the global climate and distant "teleconnections." Evapotranspiration has declined across much of the globe, but especially in tropical areas, reducing the atmospheric moisture, which in turn reduces rainfall. Deforestation and degradation lead to significant climatic changes especially at local and regional scales, affecting temperature, rainfall, storm tracks and intensity, cloud formation, and carbon storage. There is increasing concern that in some parts of the world, where deforestation and degradation are sufficiently high, such as the Amazon Basin, forests could be nearing a "tipping point." If this unknown point was reached, the climate over the entire region, in this case, the Amazon, would fundamentally shift, changing forests to savannahs, and dramatically impacting regional, and even global climate and leading to innumerable other negative impacts.

4. Forests and Freshwater

Tropical forests:

- affect the quality, storage, and delivery of freshwater – to all users, at multiple scales, from groundwater, to rivers, to rainfall.
- improve water quality by preventing erosion and sediments flows to rivers (important for fishing, irrigation, and hydropower) and by removing pollutants from water flowing to streams.
- regulate water flows by slowing rainfall and allowing more water to filter into the ground.
- retain and release water during dry seasons, making them important to water availability. Deforestation leads to longer dry seasons and less available water in dry seasons.
- include highly-threatened cloud forests, which are vital for downstream water supply, especially for many urban areas and dams.
- increase stream, river and coastal health by reducing pollution and sediments, decreasing temperatures from shade, and capturing and burying vast stores of carbon.
- restoration with native species increases the moisture available (evapotranspiration) and reduces the length of the dry season once trees are established.

Tropical forests affect the quality, storage, and delivery of freshwater. While the issues of quality are understood well, debate remains on whether forests act more as pumps (giving water back to the atmosphere) as sponges (soaking and holding water), as both, or neither (see Ellison, Futter, and Bishop 2012). This debate is heavily influenced by the inherent scientific and methodological challenges in understanding complex systems where it is hard to have perfectly matched sites for comparison, where impacts happen at over large or distant geographic scales, and where time lags matter. Perspectives on tropical forests and water storage and supply are also closely linked to analysis and modeling of climate (e.g. what are natural patterns of rainfall and ET) and impacts for LULCC. Better understandings of the climate mechanisms described in the previous section (especially of the biotic pump theory), will influence future views on the ecohydrology of forested systems. The major mechanisms of how forests provide water services is given below.

A. Forests and Clean Water

Water is full of chemicals, nutrients, sediments, salts, and even pathogens (Brauman et al. 2007). Healthy forests are the most effective land cover in reducing sediments in water (Hamilton and FAO 2008). Forests improve water quality from when the first raindrops hit by preventing some sedimentation and erosion. But there are many other mechanisms through which forests also improve water quality. At broad scales, pollutants are removed from all water that trees restore to the atmosphere through transpiration. Forests also have many pathways for slowing water flow, increasing infiltration by soils. Pollution is removed from water flowing overland and into groundwater as part of the infiltration process, with vegetation, leaf litter, microbes and soils all removing or biochemically transforming contaminants (Brauman et al. 2007; Hall et al. 2011; Acreman et al. 2012). Recent research is also showing that higher biodiversity leads to more efficient ecosystem services. For example, streams flowing from, and through, tropical forests clean pollutants better than less biodiverse streams (Cardinale 2011).

Forests provide clean water by preventing sedimentation. Erosion is a natural process, worsened by human activities that remove the vegetation holding soils in place, that allow soils to dry out and blow away, or that compact or harden soil (e.g. by grazing cattle). Erosion and compaction, common to deforested areas, reduce soil health and how well water can infiltrate into the soil, and the capacity for soils to store and conduct water. Healthy tropical forests provide a high degree of water infiltration with little erosion or surface runoff (Calder and Aylward 2006). Erosion into water sources becomes sediment, and sedimentation can: "reduce reservoir capacity; impair water for drinking and domestic or industrial uses; obstruct navigation channels; raise river beds, which reduces the capacity to handle water safely; adversely alter aquatic habitat in streams; fill the spawning grounds of fish; wear down turbine blades in power installations; and cause landslides, which damage people and their structures and block channels, resulting in floods" (Hamilton and FAO 2008).

Maintaining forest cover also precludes other land uses (agriculture, mining, transport) in watersheds that are associated with greater pollution. For example, converting Indonesian forests to oil palm plantations has dramatically reduced the quality of freshwater to poor farming communities by hugely increasing sediment (up to 550 times more that natural forest streams), increasing the water temperature (4 degrees Celsius), and increasing the rate of oxygen use in streams (a measure of stream health)(Carlson et al. 2014).

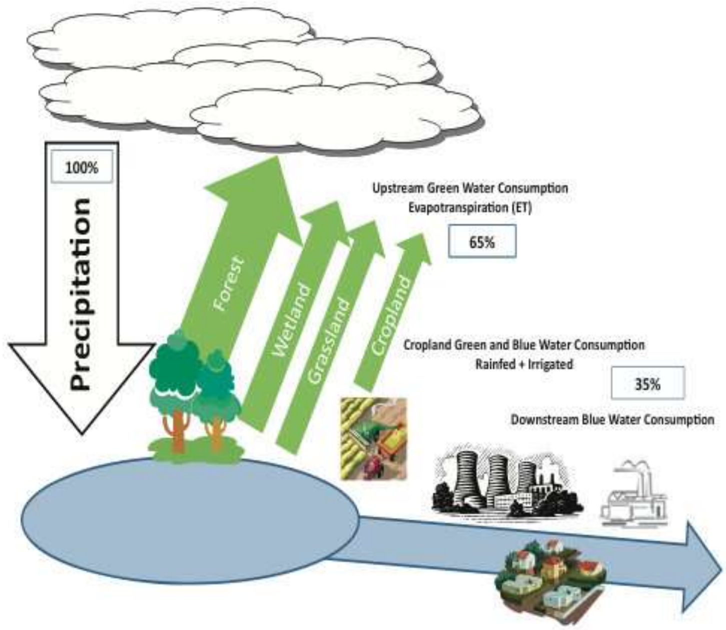
It is therefore common to find upland watershed protected areas established or maintained to protect water quality for cities such as Harare, New York City, Quito, Bogota, and Singapore (Dudley and Stolton 2003; Hamilton and FAO 2008). For example, the economic benefits of conserving healthy forests have long been recognized in safeguarding the water supplies of cities. In fact, drinking water for about one-third of 105 of the world's largest cities originates in protected areas (Dudley and Stolton 2003), including Quito, Ecuador. Home to 1.6 million people, Quito sources most of its drinking water from two protected areas, the Cayambe Coca Ecological Reserve and the Antisana Ecological Reserve, which contain 520,000 ha of grasslands and cloud forests. In the late 1990s, Quito's municipal government partnered with a local non-profit called Fundación Antisina to establish a trust fund to purchase conservation easements and manage the city's watershed, with support from The Nature Conservancy and the US Agency for International Development (Postel and Thompson 2005). Fees paid by water service users, including the city water utility, hydropower producers, irrigators, and commercial flower plantations, are invested into the fund. Other cities in the greater Andean region, including Bogota, have established similar funds (Hanson et al. 2011).

B. Forests and Water Availability

Perhaps the most commonly held view in hydrology is that forests <u>use</u> more water than other types of vegetation (e.g. plantations or agriculture) (e.g., Bruijnzeel 2004) and they have "lower surface runoff, groundwater recharge and water yield" (Calder et al. 2007), which reduces the amount of water that flows to aquifers or rivers – water that people can access or use. This "demand side" perspective (Ellison, Futter, and Bishop 2012) sees forests as consuming water and competing with other uses, and even sees some potential benefits in converting forests to other uses in places facing water scarcity (Andréassian 2004; Bruijnzeel 2004; Kaimowitz 2004; Calder et al. 2007; Lele 2009).

Compelling evidence suggests that this conventional wisdom is too narrow (Ellison, Futter, and Bishop 2012). Demand-side studies at the scale of small watersheds correctly show that forests use more water and reduce flows for other uses. However, Ellison, Futter, and Bishop 2012 note that these studies ignore the supply side – the fact that evapotranspiration to the atmosphere is an important service, and that this results in rainfall elsewhere, at local, regional and global scales. They suggest thinking of flows as blue versus green water, as shown in Figure 6. Blue water represents the demand side, what is available for human use, while water used by plants through evapotranspiration is shown in green. As shown in figure 6, forests return the greatest ET back compared to other vegetation, as shown by the width of the green band. "Green" water is both used by vegetation and released as rainfall, so it is also "useful" to other sectors, such as agriculture. Accurate measurement of forest and water flows requires looking at broad scales and accounting for both green and blue water flows, as shown below.

Figure 6: Green and blue water flows

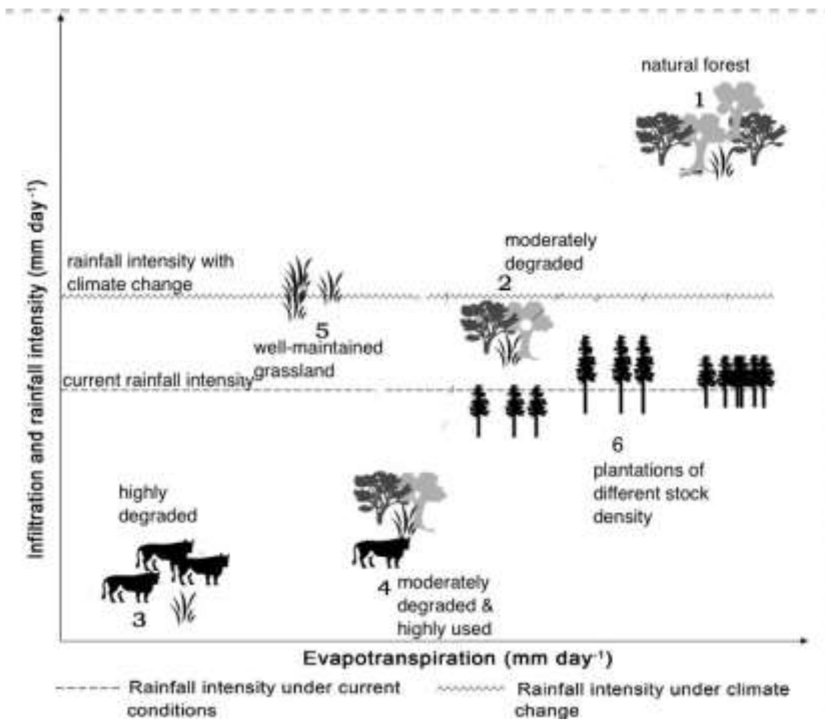


Source: Ellison, Futter, and Bishop 2012

But green water pathways (ET), are rarely counted in studies of water supply, or when it is, results may show that tropical forests use more relative to other land uses. Accurate understanding of forests and water supply must therefore include both green and blue water flows—at scales that can appropriately capture areas over forests with high ET and the downstream areas that receive rain (Falkenmark 2008 and Hoff 2010 in Ellison, Futter and Bishop 2012).

Emerging research looking at larger geographic scales and considering both supply and demand side arguments, gives very different findings about forests and water than findings from conventional studies. In the Western Ghats, for example, the amount of precipitation returned as groundwater recharge was highest in natural forests, with groundwater recharge rates of 46-70 percent for natural forests, 39-56 percent for acacia plantations, and 14-45 percent for degraded forests (Krishnaswamy et al. 2013). Regenerating forests provided enhanced rainfall infiltration, overriding the greater water use of the forests themselves (Beck et al. 2013). Figure 7 compares these findings for evapotranspiration and infiltration from natural forests (highest in both), to other forests, grasslands, and pasture. It shows that converting natural forests to young plantations may show equal evapotranspiration, but there is lower infiltration, so groundwater recharge declines over time. Converting forest to pasture, with high-density grazing leads to reductions in both.

Figure 7: Diagram Comparing evapotranspiration and infiltration in Natural forests to other Land Uses.



Source: adapted from Krishnaswamy 2013: 206

Clean, abundant, and reliable water is critical to hydropower generation. A recent study in the Amazon basin demonstrates the debates over scale, deforestation, and water flow (Stickler et al. 2013). The study looked at the Belo Monte energy complex, currently being built on the Xingu River, and which will be one of the world's largest hydroelectric plants when completed. The study estimated the impacts of deforestation on Xingu river discharge, critical for energy production. Analysis of only localized deforestation at rates of 20 percent and 40 percent of the area showed that discharge would increase by 4 percent and 10 percent, consistent with other demand side studies, suggesting that deforestation increases runoff and surface water flow. But when broader scale deforestation in the Amazon basin was considered, the results were reversed, and current deforestation rates of 15 percent reduced water discharge up to 13 percent and forest loss of 40 percent decreased discharge up to 36 percent due to declines in rainfall regionally -- suggesting that energy production could be compromised. This study demonstrates that scale effects can lead to very different results and shows the importance of accurate modeling of forest area, ET, and rainfall for understanding water supply. A meta review for the Amazon supports this analysis of broader deforestation and declining precipitation (Marengo 2006), although debate remains.

Forests also appear to retain water and then release it over the dry season when it is most needed. Water basins with higher forest cover (68 percent) had the least change in flow during the dry season when compared to nearby watersheds converted to grasslands (Roa-García et al. 2011). Similarly, forests in central Panama released more water than grasslands and mixed-use landscapes during the late dry season, showing their importance in regulating water flow in seasonal climates (Ogden et al. 2013). Transpiration, groundwater recharge, and water flow were sustained longer in the dry season in the Western Ghats where there was the highest forest cover (Krishnaswamy 2013). The authors note the critical importance of protecting natural forests in headwater areas, both to maintain humidity, precipitation, and especially water flow during dry seasons.

In contrast, multiple studies have shown that deforestation in the Amazon, Cerrado, and Yellow River in China all made the dry season last about a month longer (including water flow and rainfall, affecting all sectors that depend on water (esp. agriculture and energy)(Ellison, Futter, and Bishop 2012; Pires and Costa 2013). A study spanning 50 years at the regional scale in China showed that dry season river flows increased after large-scale reforestation, suggesting that forest recovery can help redistribute water from the wet season to the dry season, providing more when it is needed most (rather than competing for it) (Zhou et al. 2010). This is because restoration of secondary forests restores soil health, even though this process may take several decades (Bonell et al. 2010; Ghimire et al. 2014).

Cloud affected forests are few in size and number, but are highly threatened and are critical to providing a clean and stable water supply and other ecosystem services. Cloud forests also are very important in some parts of the world for the amount of fog that they intercept, especially in the dry season (Mulligan and Burke 2005; Mulligan 2010). Fog can represent up to 50 percent of water flow in dry coastal areas of Chile and southern Peru, with 10 percent of flows being more common in parts of Colombia and the eastern Andes of Bolivia, Peru, and Ecuador. A study of Honduran cloud forests found that groundwater recharge was higher and watershed discharge was four times higher on a per area basis in cloud forests compared to other forested watersheds despite similar rainfall and hydrology (Caballero et al.

2013; Mulligan and Saenz 2013). Cloud forests are tremendously important to hydropower and dams, even though they only occupy 4.4 percent of the land area that drains into dams), they hold between one-fifth and half of the surface water balance of dam watersheds (Mulligan and Saenz 2013).

C. Riparian and Coastal Forests and Water Flows

There are strong links between tropical forests, the rivers and streams that flow from and through them, and the coastal areas where these rivers run to the ocean. The role of forests in the water cycle has been described in prior sections. This section briefly describes some of the important features of forests along waterways (riparian forests) and the coastal areas where these waterways emerge.

The riparian forests and vegetation lining riverbanks are especially important for water quality and flow (described in Section 4-A). They help anchor soils and reduce erosion and sedimentation, especially from overland flows and filter out pollutants before they reach streams (Acreman et al. 2012). Of vital importance to both biodiversity and the billions of people that depend on artisanal fisheries is the role of riparian forests in regulating temperature, for both microclimates and regional ones. Temperatures of streams in oil palm plantations in Indonesia were 3.9°C higher for young and 3.0°C warmer for mature plantations than in streams through intact forest – with similar findings for pastures in Costa Rica (Lorion and Kennedy 2009; Carlson et al. 2014). There were also differences in the levels of oxygen in both sites. Fundamental changes to the level of oxygen, the temperature, and the water quality all strongly affect fisheries, generally reducing the yield of fish and the species composition of fish populations (Lorion and Kennedy 2009; Carlson et al. 2014).

Hydrological connectivity is the multiple and often long connections among creeks, lakes, streams, and rivers. Streams are connected to larger rivers, which flow out to the sea, so that upstream changes have "ripple" effects elsewhere (Pusey and Arthington 2003). For example, in many forested river systems, the large amounts of leaf litter, fruits and seeds falling from riparian forests into rivers are important to the diet of fish (Castello et al. 2013; Gonçalves Jr et al. 2014). There is also a balance between the water quality and flow from streams to the estuaries and mangroves and even offshore reef systems or seagrasses. Upland deforestation near rivers that leads to increased erosion and sedimentation can flow through streams, emerging in coastal zones and damaging the health of tidal marshes, mangroves, and reefs. Similarly, changes in the quantity, timing, or flows of water can affect the salinity of coastal forest systems, and thus their health (Valiela et al. 2013; Yáñez-Arancibia, Day, and Reyes 2013).

Coastal forests, especially mangroves, have incredibly high value for both conservation and human well-being. Mangroves only cover 0.5 percent of the global coastal area, but they store a huge (and until recently uncounted) amount of carbon (Alongi 2014). One recent discovery was the huge amounts of carbon stored in what has been termed "ocean margins," with some estimates suggesting that coastal estuaries, wetlands and mangroves reach as high as 90 percent of global carbon burial (Bauer et al. 2013). For example, studies of mangroves in the Indo-Pacific found an average 1,023 Mg/ha (Donato et al. 2011), while healthy mangroves in four Central African countries stored 1520± 164 Mg/ha (Ajonina et al. 2014).

The rich carbon stored in mangroves is not just from the leaf litter from mangroves themselves, but from the huge amount of organic matter that they trap. Especially in healthy and undisturbed ecosystems, large amounts of organic material travel down rivers and are trapped by mangroves, where they become stored carbon. The "cleaning" function that mangroves perform is important for trapping downstream sediment and stopping it from flowing offshore, where it could damage marine ecosystems (e.g., reefs and seabed grasses). It also helps the mangroves build shoreline, adding to their protective value in buffering coastal waves and storms.

Climate change has the potential to seriously impact this complex hydrological connectivity in a wide variety of ways. Changing microclimates in forests affects stream temperatures and flows; water warming changes fruit and leaf litter decomposition patterns, affecting the availability of food to fish and the concentrations of oxygen in the water. These in turn affect the ability of freshwater systems to degrade waste and maintain productivity. If less freshwater flows from river, coastal waters will become saltier– changing the conditions that coastal forests are used to and thus impacting their health and ability to provide a full range of ecosystem services (Anderson, Lockaby, and Click 2013). Not surprisingly, destroying marshes, mangroves, and seagrasses releases an estimated 0.15–1.02 billion tons of CO_2e, equal to 3–19 percent of global deforestation, with economic damages of $6–42 billion annually (Pendleton et al. 2012).

5. Forests and Natural Disasters

Tropical forests:

- mitigate disaster impacts by preventing erosion and gullying, limiting localized landslides, reducing flooding, and even lessening wave impacts.
- channel water, and prevent or reduce erosion and the risk of landslides and debris flows, especially in hilly areas, because of their complex root systems.
- destruction increases landslide intensity, frequency and extent, especially on slopes exceeding 25° or when roads are cut into forests on steep hillsides.
- reduce the frequency, magnitude, duration, and volume of floods – especially smaller floods.
- in coastal areas, such as mangroves, reduce the impact of waves from peak tides, storms, storm surges, smaller tsunamis and even extreme wind-driven waves from tropical cyclones, and may reduce some impacts from large tsunamis (e.g. Indian Ocean 2004 and Japan 2011).
- resist fire given their high humidity levels and frequent rainfall, so healthy tropical forests experience only limited fire.
- are highly affected by fire, which is becoming more frequent with habitat fragmentation, more forest edges, and less healthy forests – leading to a downward and vicious cycle of fire and permanent forest loss.

Natural disasters take a huge toll on life and property in the tropics. Tropical forests can't stop natural disasters from happening, but there is growing evidence that they can prevent erosion and gullying, limit localized landslides, and reduce flooding, and even mitigate tsunami impacts (Renaud, Sudmeier-Rieux, and Estrella 2013). Their role in mitigating erosion and landslides is especially important in hilly or mountainous areas, as mentioned in the case of Haiti. Coastal forests—mangroves in particular—can buffer wave action, a critical element of typhoons and tsunamis. Healthy, intact forests are also more resistant to drying and diseases and thus to fire. Finally, forests can reduce some types of flood events, although there is debate over this. This section summarizes the state of science on how, where, and when forests prevent or mitigate the effects of natural disasters. It also addresses the impacts of habitat transformation and climate change on these forest ecosystem services.

A. Landslide Prevention

Landslides occur naturally. In much of the world they are closely related to earthquakes, as tropical areas with high seismic risk frequently also have steep slopes. But landslides unrelated to seismic risk are increasing due to the deforestation and degradation of tropical forests on steep slopes (Guns and Vanacker 2013). Converting forest areas to other uses—or even selectively logging them—increases erosion and the rate and extent of landslides.

Certainly, there are mountainous areas where the landslide risk is low, but in much of the tropics, especially in areas with slopes over 25°, there is a strong link between deforestation, surface erosion, and landslides.

Deforestation can lead to surface erosion, which is then linked to shallow, rapid landslides that are triggered by a single event of heavy rainfall. Large-scale landslides happen over a wide area and are more likely to occur after soils have accumulated lots of water over a longer-term, such as a monsoon season. Forests can limit or reduce both shallow and large-scale landslides, although their role in limiting erosion and shallow landslides is better understood (Sidle et al. 2006). Forests reduce landslides because:

- Root systems anchor soils, providing soil stability. Deep roots act as deep anchors, while shallower root systems keep soils in place. Thick, buttressed roots that cross the forest floor act as breaks.
- Deep root systems act as channels, facilitating water infiltration and reducing landslide risk.
- Moist soils are healthier, with greater soil cohesion. The soils under the canopy stick together, giving greater strength to the soil profile (Runyan and D'Odorico 2014). Forests reduce the intensity of rainfall (up to 66 percent), which reduces the damaging impact of hard and heavy rain onto soils as well as erosion and debris flow (Greenway 1987).
- Forests quickly remove excess water through evapotranspiration. In forests, the combination of evaporation from water sitting on the leaves and branches, and transpiration (the water that efficiently moves from the soil up through root systems, which the tree then recycles puts back into the air) is substantial, reducing landslide risk (DeGraff et al. 2006). In contrast, imagine a heavy, waterlogged steep slope with few trees, where the rain falls hard and damages or loosens soil, and where the water sheets downhill quickly. There is nothing to buffer the rainfall or pull the water underground. When the sun comes out, some water will evaporate, but not much, increasing the landslide risk.

Deforestation can increase landslide intensity, frequency, and extent. Removing rainforest on slopes, for roads or crops, can lead to a vicious cycles. The cleared area has more erosion, which happens more frequently over time, increasing the eroded area. This can lead to small landslides, which also increase in area and frequency, with a cycle of ever-widening erosion.

The slope is then more likely to slide, and time to the next landslide is shorter. Modeling shows that deforestation data may be used to predict landslides. For example, in 1999, a tropical storm moving over three Mexican states affected 200 municipalities and nearly 1.5 million inhabitants, and resulted in 263 deaths from landslides, of which 80 percent were linked to deforestation (Alcantara-Ayala 2004; Alcántara-Ayala, Esteban-Chávez, and Parrot 2006). A similar study in Puerto Rico confirmed that it is possible to predict massive impacts from landslides and flooding from deforestation (Larsen and Torres-Sanchez 1998). However, forest cover cannot stop landslides triggered by seismic events or extreme events, such as torrential rainfall from typhoons, which may happen more frequently given climate change.

Downslope areas can also be affected, as the soils and small landslides move down the slope, forming a big pile of unstable, loose material (Stokes et al. 2014). With a triggering event, such as strong rainfall, an earthquake, or brush fires, what is called a "debris flow" can happen. While there can be small debris flows that only cover a small area, others can become quite large. All of the loose soils that have accumulated, along with larger objects (e.g., small trees and logs), start moving down the slope, gathering more soil and objects, and intensifying their weight, size and impact. They hurl down hillsides and may not stop until reaching a plateau, valley, or river. The damage depends on their size. Healthy forests can prevent small debris flows from ever forming and can even stabilize smaller ones (Guthrie et al. 2010). When small debris flows do occur, tree roots can hold the flows so that they do not build and gather strength. The areas where rainfall-induced debris flows are most common are: coastal areas around the Pacific Rim; New Zealand and other large Pacific islands; Southeast Asia; the Caribbean, and parts of North and South America (DeGraff et al. 2006).

The higher up on a hillside that trees or vegetation are cleared, the worse the impacts of debris flow are downhill, since the weight and size of debris flows has room to increase. Roads, especially non-engineered ones that are carved through rainforests (e.g., logging roads), can have incredibly high risk of failure, triggering landslides or debris flows both above and below the road. Both types of failure are commonplace since there is little holding the exposed soils in place. These erosion losses from roads can be one to two orders of magnitude higher than in undisturbed forests on steep land (Sidle et al. 2006; Brenning et al. 2014).

The bottom line is that most other land uses are less effective than tropical forests in reducing erosion and preventing shallow landslides. Disturbing forests on steep slopes and converting them to other uses begins damaging and often cascading processes. While vegetation in flat tropical forests can regenerate quickly, deforestation and previous landslides on slopes make regeneration more difficult and costly since erosion limits the time seedlings have to grow and enhance soil stability. Adding to the evidence that leaving forests intact is better, even where there is regeneration, the root strength of new forests will be weaker than the original forest even twenty years later. Where climate change is likely to increase storm intensity or duration, replanted forests may not be strong enough to withstand rain and winds, increasing landslide risk (Guns and Vanacker 2012).

Once forests are cleared on steep hillsides, it is better to use these lands for forests or fields, than using them for pasture or leaving them alone. When forests are converted to pastures, for example, the slope stability rapidly and permanently declines (Guns and Vanacker 2012). Conservation agricultural practices (reduced and contour tillage, strip cropping, etc.) reduce erosion but are less good at reducing landslide risk (Sidle et al. 2006). Agroforestry is more than an order of magnitude better at reducing surface erosion than monoculture plantations with no ground cover. Restoring forests on steep slopes is, from a disaster perspective, worthwhile and perhaps essential in some areas, but will never be as effective as preventing deforestation. Finally, as climate change causes glaciers to melt, healthy forests on steep slopes will have an important function in absorbing heavy snowmelt and rainfall and limiting landslide extent and intensity.

B. Forests and Flooding

There are divergent views about forests and flooding across multiple dimensions, including "the frequency, magnitude, duration, and volume of floods" (Alila et al. 2009). Floods can affect either the shape or flow of rivers—both of which cause them to overflow their banks (Calder and Awylward 2006: 3). Changes affecting the form happen if channels are blocked or sedimentation levels are high, and sediments can form up to 17 percent of floodwater volume (Calder and Awylward 2006). Changes in flow typically result from large storms.

The basic ideas about why forests should reduce flooding are simple (Bruijnzeel 2004; Brauman et al. 2007; Laurance 2007). First, forests have higher levels of evapotranspiration, and all the extra water that returns to the atmosphere is not available to cause flooding. Second, more forest means more water will go into the ground (the sponge), rather than run off to streams and rivers, so there is less water flowing and causing floods. Third, forests have good soil health, which increases the amount of water they absorb, and they also reduce soil erosion compared to other uses, so less soil fills up the streams and rivers that reduces both their form (more sediments) in the water and also making them shallower and easier to flood.

Foresters have been looking at the issue of forests and flooding for more than a century, and the conventional wisdom is that forests reduce and mitigate small and local floods. But there is less agreement on the relationship of forests and extreme flood events, flooding at broader catchment scales and forest cover change and flooding (FAO 2005; Alila et al. 2009; Bradshaw et al. 2009; Van Dijk et al. 2009), a critical issue when considering the costs and benefits of reforestation programs, for example (see Bradshaw et al. 2009). Recent evidence is suggesting that forests *do* provide flood protection, even for larger scale flooding. Alila and coauthors (2009) argue that the view that there is no relationship with larger scale flooding may be wrong for methodological reasons[11], and that forests may prevent large scale flooding (see Alila et al. 2009).

Using data from 56 developing countries for 1990 to 2000, Bradshaw and coauthors (2009) show that the chances of flooding frequency are higher if there is less natural forest, and more likely after natural forest area loss (after accounting for rainfall, slope and degraded landscape area). They found that a 10 percent decrease in natural forest area increased flood frequency between 4 percent and 28 percent and total flood duration by 4–8 percent. However, they excluded extreme events and their findings have been debated (e.g. Van Dijk et al. 2009). Other studies have shown that more forest cover helps mitigate moderate rainfall events (i.e., more frequent), but might not help with extreme events (Bathurst et al. 2010). Yet a comprehensive study of nearly 450 tropical storms, including extreme events, in forests and pastures in the Panama Canal Watershed that found that the forested catchment had 35 percent less total runoff and smaller peak runoff during record flooding than the non-forested catchment (Ogden et al. 2013). These and other recent studies employing novel methodologies or larger scales suggest that forests may be very important in flood prevention and mitigation.

[11] Studies fail to: account for changes in flood frequency (so they also miss changes in magnitude); they also miss non-linear and inverse relationships; and methodologies look at means mask variance.

C. Mitigation of Coastal Waves and Tsunamis

Coastal forests, especially mangroves, are immensely valuable for the variety of ecosystem services they provide to billions of people (Cochard et al. 2008; Feagin et al. 2010; Bell and Lovelock 2013; McIvor et al. 2013). After two extreme events in a short time-span (the 2004 Boxing Day tsunami in the Indian Ocean and Hurricane Katrina in 2005), attention turned to the role of coastal vegetation and forests in reducing the impacts of extreme events affecting coastlines. Debate ensued over when, where, whether and how coastal forests can serve as "bioshields," mitigating impacts from both moderate and extreme events (Feagin et al. 2010). While the mechanisms for how forests reduce coastal impacts are relatively clear, there is discussion over the magnitudes of impacts (Cochard et al. 2008; Feagin et al. 2010; Bell and Lovelock 2013; McIvor et al. 2013).

There is general agreement that mangroves can reduce the impact of waves from peak tides, storms, storm surges, and even extreme wind-driven waves from tropical cyclones – events where the wave height is small (Baird and Kerr 2008; Cochard et al. 2008; Yanagisawa et al. 2010). The mechanisms are relatively simple. The trees themselves help slow and break up tidal and wave energy, critical as climate change worsens storms and raises sea levels. Coastal forests also trap sediments, increasing coastal elevations (McIvor et al. 2013). How well trees can slow storm surges or stop waves, depends on many factors, such as the composition of trees (e.g., mangrove or land-based forests), the species composition (e.g., natives or exotics), and the stand size and density (Das and Vincent 2009; Feagin et al. 2010; McIvor et al. 2013).

Just as the on-shore conditions matter, so do the characteristics of the waves. Tropical storms surges have short wave height, shorter periods between them, and the energy is concentrated near the surface. A laboratory experiment found that how well mangroves reduced wave *impact* depends on whether the water is high (hitting the trunks and canopy) or low (hitting the roots)(Ismail, Wahab, and Alias 2012). Even a 1-meter width of mangroves could reduce water impact by 23–32 percent for high water and 31–36 percent for low water, with a 3-meter width reducing impacts by 39–50 percent during high water and 34–41 percent during low water conditions. These laboratory findings were built on other similar studies (Mazda et al. 2006). They are supported by a field-based study of the impact of a large cyclone that struck hundreds of villages in Odisha, India in 1999 (Das and Vincent 2009), where wider mangroves between villages and the coastline significantly reduced deaths.

Mangroves also reduce wave impact by reducing wave height. A wide area of mangroves (500 m) can reduce the height of small wind and swell waves between 50 percent and 100 percent (McIvor et al. 2013). For smaller waves, they suggest that each inland kilometer of mangrove reduces storm surge water levels by between 5 cm and 50 cm (McIvor et al. 2013). As part of coastal zone defenses, it makes sense to have mangroves in front of sea walls or dykes, as they reduce the height and strength of storm surges, reducing damages to infrastructure.

Disagreements are stronger around the value of coastal forests for large-events, such as major tsunamis. After the 2004 Indian Ocean tsunami, there was extensive debate on whether mangroves and other coastal forests offered protection. Consensus seems to be emerging that it depended both on the off-shore conditions (e.g. presence of coral reefs or sea bed grasses, shallow or deep seabed), the on-shore conditions (the type and characteristics of forests), and the conditions of the tsunami itself. For example, in the 2004 tsunami, waves in India and Sri Lanka were smaller than in Banda Aceh, Indonesia where they reached up to 30 meters. A Sri Lankan study found that coastal forest plantations reduced the tsunami force, velocity, and depth and were especially effective when there were no gaps in the forest (Samarakoon, Tanaka, and Limura 2013). There is some consensus that mangroves and other coastal forests can help dissipate the energy from tsunamis when the wave height is small and the timing between waves is short (Cochard et al. 2008; Yanagisawa et al. 2009).

However, many authors note that tsunamis or other extreme events with very high winds and high storm surges may overwhelm and destroy mangroves and other coastal forests (McIvor et al. 2013). One study used data from the 2004 Indian Ocean tsunami to look at the strength of mangroves, finding that a 500m wide young mangrove (10 years old) could reduce a 3-meter tsunami's force by approximately 70 percent, but a 4-meter tsunami would destroy most of the mangrove. However, most (80 percent) of an older stand of mangroves (30 year) could survive a 5-meter tsunami and absorb 50 percent of its force (Yanagisawa et al. 2010). It is likely that the debate will continue, since recent findings suggest that mangroves can reduce damage even from large tsunamis. In Banda Aceh, coastal vegetation significantly reduced human casualties by an average of 5 percent (Bayas et al. 2011), despite the extreme wave heights there. A study of the Great Japan tsunami impacts suggests that for a 10-meter high tsunami, a 600-meter-long coastal forest reduced the washout region of houses at the coast by approximately 100 meters (Tanaka et al. 2013).

Events such as tsunamis are relatively rare, but reducing the impact of storms and surges will become increasingly important as climate change projections predict more intense tropical storms, with higher wind speeds and destructive energy (Christensen et al. 2013). Mangroves can protect soils and increase overall elevation of areas, vital in a world of rising seas. They can reduce storm damage, projected to increase with future climate change. Feagin and coauthors (2010) conclude, "Coastal vegetation such as mangrove ecosystems is critical to the resilience and vitality of many coastal social-ecological systems and we believe that their conservation is necessary".

D. Intact Forests Are More Resistant To Fire

Natural fires happen very rarely in tropical forests, but they do happen (Cochrane 2003; Bond and Keeley 2005; Bowman, O'Brien, and Goldammer 2013). Both historical records of tropical forest fires and analysis of charcoal found in soils show that fire is possible. But unlike with some ecosystems where fire is a frequent part of natural cycles, fire intervals in tropical forests may be in the thousands of years (Cochrane 2003). The key conditions for significant wildfires are an ignition (e.g., lightning strike) and enough dry fuel to ignite and combust (Cochrane 2003; Herawati and Santoso 2011; Verma and Jayakumar 2012). Many conditions present in tropical moist forests limit the spread of fire despite frequency of lightning as part of tropical storms. The first is exactly that: lightning is often a component of tropical rainstorms, so even if there is a strike, the rain helps put the fire out. The second is the high levels of moisture that are present in closed canopy forests, even during the dry season (Cochrane 2003; Hoffmann, Orthen, and Nascimento 2003). The deep taproots of some species provide moisture to the surrounding vegetation.

Fire within closed canopy forests is also inhibited because forest gaps are quickly filled, which reduces the potential for drying in exposed areas. Gaps that do allow light may also lead to an increase in vegetation, which, if dry, would serve as a fuel source. One researcher also noted, however, that the high area in leaves in tropical forests compared to wood also helps them resist fire (Dantas, Batalha, and Pausas 2013). One can think of this green to brown ratio as being very different than in temperate forests, where the trees themselves can serve as potent fuel for fires (Cochrane 2003). The high canopies, high leaf ratio, and large stem diameter—as well as the huge variety of species found—makes a tropical forest fire very different from a temperate forest fire where most trees share a similar height and condition (Hoffmann, Orthen, and Nascimento 2003; Brando et al. 2012).

When fires do occur, they behave very differently in tropical forests than in other areas (Cochrane 2003; Brando et al. 2012; Bowman, O'Brien, and Goldammer 2013). Under normal (non-drought) conditions, fires move slowly through the understory, at only 15-25 meters per hour (Brando et al. 2012). Rainforest fires often seem to be small, slowly burning the leaf litter. They also tend to be extinguished at night, when the humidity in the forest increases. In Australia for example, closed-canopy forests were associated with no fires, or low-intensity ones (Trauernicht et al. 2012).

If the conditions (e.g. persistent drought) are in place for a fire, they can lead to high tree mortality, since tropical moist forest trees are not adapted to deal with fires (Barlow et al. 2003; Barlow and Peres 2008). Meyn and coauthors discuss large, infrequent wildfires and note that such fires are typically limited in tropical moist forests, but when they do occur they may be important to biological selection, given their impact, noting that the tropical forest fires in Brazil and Indonesia in the 1980s and 1990s "might be among the largest biological selection events in modern history"(Meyn et al. 2007).

Modeling forest fires in tropical forests had proven difficult because until recently they were infrequent enough that basic data to determine fire risk was missing (Cochrane 2003; Soares-Filho et al. 2012). For example, measures of minimum fuel load threshold for a forest to catch fire did not exist, and little is still known about the variety of chemical compounds, gases, and aerosols that are found in tropical forests (Cochrane 2003). Most of the studies that are modeling fire are doing so in the context of LULCC or forest degradation, and there are few that adequately measure the behavior of fire (e.g., Silvestrini et al. 2011).

However, land-use change, forest fragmentation, and the presence of edges and forest degradation are now increasing the number of fires, the intensity, and the fire risks, especially for the Amazon (Barlow et al. 2003; Meyn et al. 2007; Silvestrini et al. 2011; Lima et al. 2012; Soares-Filho et al. 2012; Yocom and Fulé 2012; Adams 2013; Marlier et al. 2013; Xaud, Martins, and Santos 2013; Brando et al. 2014). A number of impacts are already evident, and it appears that in some places tropical forests may be nearing a tipping point of higher fire risk. Fires in one part of the Amazon during droughts were more intense and covered more area (12 percent) compared with 0.84 percent in the non-drought years (Tscharntke et al. 2012). Previous fires and logging influence fire by reducing canopy cover and evapotranspiration, which increases the temperatures during the dry season and lowers humidity. They also promote greater air exchange between open fields and neighboring forests, further drying them out. Any extractive forest uses also create gaps and edges, which are drier and increase fire intensity. Greater fragmentation leads to more drying, which leads to a higher risk of fire, and a more intense fire if one breaks out.

Climate change has a huge potential to increase the number of droughts and fires across tropical forests. Several recent studies point to feedback loops – and the ways that fires are intensifying in places where they should be highly unusual events. For example, the Xingu River Basin is a seasonally dry area of the Amazon, and about 39 percent of the Amazon experiences seasonal drying. Much of this area, known as the "arc of deforestation," has already experienced fragmentation, drought, and fire. A study (Brando et al. 2014) combining both experiments and field evidence found that links exist among extreme weather events, and widespread and high-intensity fires, resulting in changes in forest structure, dynamics, and composition. It seems that fires are already affecting parts of the Amazon with a long dry season, but the risk of fire and permanent change to humid forests is increasing given human impacts leading to recommendations for large blocks of undisturbed forest (Brando et al. 2012; Soares-Filho et al. 2012; Brando et al. 2014).

6. Forests and Biodiversity Interactions

Tropical forests:

- have higher biodiversity than any other type of forests, holding 2/3 of all land-based species even though they only cover 5% of the Earth's land area.
- biodiversity is the foundation for many of the ecosystem services delivered by forests, and essential to their health and resilience.
- have extraordinary richness in some places. One 7,335 square mile Bolivian national park has over 1,088 bird species, over 12,000 plant species, 200 mammal species, 300 freshwater species, demonstrating the importance of protecting remaining intact forest blocks.
- have many rare species (called endemics) that are tied to specific locations. While species such as jaguars or tigers may roam large areas, many plant, bird, frog and insect species are found only in a small area – putting them at a high risk of extinction if forests are disturbed.
- degradation and destruction, along with other human pressures, such as hunting, are leading to a rapid and pervasive extinction of species, robbing countries (and the world) of their national patrimony.
- suffer from conversion, fragmentation and degradation, and most tropical forest areas have many species threatened with extinction, demonstrating a high urgency to protect forests and the species within them.

Biodiversity is the foundation for healthy, resilient ecosystems that can deliver a range of services. But its worldwide distribution is uneven. The number of species is small at the north and south poles, but increases as one moves toward the equator – and is highest in tropical rainforests on land and in coral reefs on sea. Tropical forests have higher biodiversity than any other forests, and they contain approximately two-thirds of all land-based species.

A recent study mapped over 21,000 species ranges of mammals, birds, and amphibians and found that the richest areas with the greatest number of species were in the Amazon, southeastern Brazil, and parts of central Africa (Jenkins, Pimm, and Joppa 2013). These areas fall into the top 5 percent richest places on the planet for all species, they include about half of all species, yet they cover only 7.2 percent of the global land area. For birds and mammals, the Amazon, Brazilian Atlantic Forest, Congo, Eastern Arc in Africa, and the Southeast Asian mainland and islands house the greatest numbers of bird and mammal species (Jenkins, Pimm, and Joppa 2013). There is a high correspondence between species richness and tropical forests.

Comparisons of diversity in tropical and temperate areas highlight the differences in richness. For example, Madidi National Park in Bolivia may be one of the most biodiverse areas in the world, holding 1,088 bird species (11 percent of the world's birds), over 200 mammal species, 12,000 plant species, 300 freshwater fish species, and 50 species of snakes in this 19,000 square kilometers (7,335 square mile) area (WCS 2012). Another slightly bigger protected area, Yasuni in Ecuador's western Amazonian is another contender, and is one of the two richest places in the world for amphibian species, the second richest for reptiles, within the top nine richest centers for vascular plants (and the top center for trees and shrubs), among the richest lowland areas for birds, high in mammal richness (particularly for bats), and very rich in fish species (Bass et al. 2010). By contrast, Everglades National Park in Florida, is a tropical wetland that is the richest area of the US mainland. But it only has 350 species of birds, 300 species of fresh and saltwater fish, 40 species of mammals, and 50 species of reptiles (Brown et al. 2006). Yellowstone National Park, a temperate protected area with high biodiversity has 322 bird species, 67 species of mammals, 1150 plant species, 15 freshwater fish, 6 reptiles and 4 amphibians (National Park Service 2014).

Looking at the richness of species found in tropical forests gives insights on forest complexity, but it doesn't give an idea if species there are rare. Some places have more unique (endemic) species than others, species that are only found in one valley, or watershed or mountaintop.

Madagascar is striking for its endemism. The whole country of Madagascar has nearly

14,000 plant species, and 95 percent of these are only found there (Irwin et al. 2010). The Brazilian Atlantic Forest has an estimated 8000 endemic plants species and over 650 endemic vertebrates (Mittermeier et al., 2005). Rarity is linked to species with small ranges that could be affected if fire, famine or disease sweep through those areas. While tropical forest blocks may cover large areas, they often have extremely high endemism, meaning each part of a forest, or each valley, may hold unique life found nowhere else on Earth. Highly specialized, rare, and endemic plants and animals are most vulnerable to human use or pressure, or climate change.

Extinction of species is fast, accelerating, and pervasive across plant and animal species, and is closely linked to tropical forest destruction and fragmentation and to direct overexploitation. Globally, biodiversity is in crisis. The Living Planet Index (LPI) found that between 1970 and 2010, there was a 52 percent decline in the population sizes of vertebrate species—mammals, birds, reptiles, amphibians, and fish across the globe (WWF 2014). While the LPI shows that temperate species declined by 36 percent between 1970 and 2010, tropical species declined by 56 percent in that period (WWF 2014: 19). Regionally, the most dramatic regional LPI decrease occurred in South America, followed closely by the Asia-Pacific region (WWF 2014).

Analyzing the patterns of threat to species also shows that they are concentrated in many tropical forests, but the patterns differ from those for richness (Jenkins et al. 2013). Nearly all tropical forest areas face some level of threat, and there are many ways of identifying conservation priorities. Looking by groups of species, Southeast Asian mainland and islands have a high proportion of threatened mammals, but threatened birds are mainly found in the Andes, southeast Brazil, and Southeast Asian islands, with amphibians widely scattered (Jenkins et al 2013). Biodiversity hotspots have been identified that look at both endemism and threat (Mittermeier et al. 2005), and only 34 hotspots covering a bit more than 2 percent of the Earth's land area hold 50 percent of the world's endemic plant species and 42 percent of all endemic terrestrial vertebrates, along with 50 percent of threatened mammals, 73 percent of threatened birds and 79 percent of threatened amphibians as endemics. All hotspots have had at least 70 percent of original habitat destroyed.

But even these numbers are incomplete. There is little known about "millions of species that are estimated to inhabit tropical rainforests, including almost all below-ground, canopy and aquatic species as well as most insects, fungi, parasites, lower plants and microorganisms" (Gardner et al. 2010). While we know most of the plants, birds and mammals, our understanding of the functional roles of many species, and how they matter in providing a range of ecosystem goods (such as food to eat) or services (such as pollination) is still incomplete, so we likely underestimate their value.

7. Forests and Food

Tropical forests:

- provide water for farming, wild pollinators essential to many crops, and wild foods used by forest-dwelling poor.
- support wild pollinators, which improve the size, quality, fruit set, and harvest stability for about 70% of global crops (although data is lacking on direct percent of wild pollinators that exclusively depend on tropical forests and contribute to the global food supply).
- host both pollinators and crop pest predators, and animals that disperse seeds – all reasons that food production in agricultural landscapes is higher when forests are nearby.
- provide wild food for many of the world's poor – especially as a safety net.
- deliver a wide diversity of plants, nuts, and animals that people eat, so people living near forests have greater dietary diversity and are healthier.
- provide meat, which is vital in providing protein, yet risks decimating species and spreading diseases.
- are closely linked to the health and productivity of freshwater river systems and deltas and coastal fisheries – which provide food for billions of people.

There is a rich and growing recognition of the connections between food security, tropical forests and biodiversity conservation. Upland forests ensure availability of water for irrigation during the dry season, pollinators are essential for many agricultural crops, and disappearing wild foods are a key dietary component for a billion people (Bharucha and Pretty 2010) and tropical river ecosystems support productive inland fisheries. While agriculture is the primary driver for tropical forest conversion, remaining tropical forests have low agricultural suitability for most crops (Gorenflo and Brandon 2005). The loss of pollinators is an important global concern – and is likely to affect food availability. Yet the further loss of forests also is likely to affect many of the world's poor, who depend greatly on foods from non-agricultural systems (e.g. nuts, fruits, leaf vegetables), both routinely and especially as a 'safety net'.

A. Forests, Pollination, Pests, and Food Crops

Tropical forests, and the wild insects and animals remaining within them, play a hugely important role in supporting the global food supply through both pollination and pest control. About 70 percent of leading global crops benefit from pollination by wild insects and bees, and pollination affects the size, quality, likelihood of fruit set, and harvest stability (Ricketts et al. 2008). Over one-third of the global food supply depends on directly on animal pollinators (Lebuhn et al. 2013). Apart from their value to global food, wild species also pollinate about three-fourths of the world's flowering plants (Ollerton, Winfree, and Tarrant 2011). Pollinating nearly 10 percent of all food crops produced for human consumption was valued in 2005 at $190.5 billion annually (Gallai et al. 2009). While most food crops consumed are wind pollinated (rice, wheat and corn), animal pollinated crops have at least a 10-fold higher economic value (Gallai et al. 2009). They also have a high nutritional value, containing most of "the available dietary lipid, vitamin A, C and E, and a large portion of the minerals calcium, fluoride, and iron worldwide"(Eilers et al. 2011). Further, wild pollination leads plants to bear more fruit and improves their nutritional content (Brittain et al. 2014; Klein et al. 2014). Unfortunately, there is no global data on the importance of tropical forests specifically for wild pollinators – i.e. what percent of global pollination is by wild pollinators that depend directly on forests. But we know that wild pollinators are vital to the global food supply, and include many species (birds, bats, rodents, lemurs, etc.) other than bees that prefer forests. A related service that has not been well assessed but that supports wild food growth is seed dispersal, where birds and animals eat seeds and drop them elsewhere.

Comparisons of pollination services in natural and plantation forests, and the impact of forest patches in natural landscape suggest that there is an important role that tropical forests have in providing pollination services. For example, larger areas of natural forest are healthier and can host both more pollinators and more predators for crop pests. The size and quality of forests thus affects nearby agricultural production – especially smallholders, since small differences in yield can matter greatly, and affects the many high value crops that depend on wild pollinators (Taki et al. 2011; Winfree, Gross, and Kremen 2011). While data is lacking to give solid numbers on which wild pollinators primarily live in forests, some studies are suggestive. For example, a global synthesis shows that 53 percent of all tropical bird species live only in forests, while less than 1 percent prefer agricultural areas. But 33 percent of the bird species that live in forests will fly to agricultural areas, providing pollination, pest control, seed dispersal and nutrients (Şekercioğlu 2012). Forest loss diminishes which species exist and which "visit" agricultural patches and provide services.

Wild insect pollinators are declining worldwide (Garibaldi et al. 2013) and this could lead to agricultural yield declines with "a potentially drastic effect on human nutrition if jeopardized" (Eilers et al. 2011). The impact could be especially significant for the rural poor in tropical countries (Steward et al. 2014). While attention has been focused on bee declines, a cause for concern, much less attention has been given to declines of wild insect pollinators worldwide. Recent studies indicate that for 41 different crop systems, pollination by wild insects was more than twice as effective than by honeybees, with the authors suggesting that honeybees should be viewed as supplementing, rather than substituting for wild pollinators (Garibaldi et al. 2013)

Wild insects can also provide important biocontrol, reducing or eliminating the need for pesticides (Tscharntke et al. 2012). A recent study of Indonesian cacao agroforestry found incredibly strong biocontrol services from birds and bats, with a final crop yield of areas distant from forest being 31 percent lower than places nearer to primary forest (Maas, Clough, and Tscharntke 2013). In Mexico, certain valuable hardwood species host insects that attack fruit fly pests, providing valuable biocontrol. The authors note that conserving tropical forests helps poor farmers reduce crop losses (Aluja et al. 2014). A study of biocontrol in Costa Rican coffee farms found that native bird predators reduced the damaging coffee berry borer beetle by 50 percent (Karp et al. 2013). They estimated that birds from forest patches prevented damages of US\$75–US\$310 ha-year^{-1} in damage, equivalent on a per plantation basis to a Costa Rican citizen's average annual income (Karp et al. 2013).

Climate change is projected to have strong, and as yet, many unforeseen consequences on the pollination and biocontrol services provided by tropical forest wildlife (Şekercioğlu, Primack, and Wormworth 2012). However, the loss of forests themselves is the most immediate concern, with climate change impacts likely stressing forest health and decreasing the quality of ecosystem services provided (Cock 2013).

B. Forests and Wild Food

Many of the world's poor depend directly on wild foods from tropical forests (Poppy et al. 2014). These wild foods are important for many reasons, but most directly is that they act as a safety net if food crops fail, income declines, or disasters natural or personal, strike. A recent and comprehensive global study (Angelsen et al. 2014) looks at the links between forests and environmental income, including forest foods. Forest foods are the second most used category of products that people derive from forests. Globally, wood fuels account for 35 percent of forest income while food accounts for 30.3 percent of forest income (Angelsen et al. 2014). However, there are strong regional differences, and in Latin America, food products constitute 53 percent of forest income. There is a high dependence on plants in Latin America (30.9 percent) compared with only 14.9 percent for Asia and 12.9 percent for Africa. Reliance on animal products is also double in Latin America (21.8 percent) the numbers for Asia and Africa.

Since tropical forests contain some of the world's highest biodiversity, it should not be surprising that people obtain and eat a wide variety of forest fruits, nuts, vegetables, mushrooms, insects, fish and other animal products. Studies of agricultural and forager communities in 22 countries in Asia and Africa have shown that people use an average number of 90-100 different food species at each site, although uses in some countries, such as India and Ethiopia, can reach aggregate totals of 300 to 800 species (Bharucha and Pretty 2010).

The high diversity of products has important nutritional implications. While people may not get a large quantity of any one food at a given time, they often have access to small portions of a wide range of foods. This diversity of foods can be incredibly important in terms of the micronutrients found. There is emerging evidence that greater forest biodiversity increases the variety of nutrients people receive, thus improving their overall health. For example, one study in Malawi found that children living in places with higher forest cover had a more diverse diet and were more likely to consume vitamin A rich foods and have less diarrhea (Johnson, Jacob, and Brown 2013). The corollary is also true: declines in forest cover led to a 19 percent drop in dietary diversity. African children living in forested areas have more diverse and nutritious diets, based on a positive relationship between tree cover and dietary diversity, especially of fruits and vegetables (Ickowitz et al. 2014). A study in the Democratic Republic of the Congo found that people consuming wild plant foods have higher intake of vitamin A and calcium (Termote, Van Damme, and Djailo 2011; Termote et al. 2012). However, these studies also found that all wild foods were collected in different settings, not just primary forest. Wild foods are also especially important as a 'safety net,' when conditions strike families making them vulnerable. For example, Malagasy farmers are particularly dependent on wild yams from forests during the 'lean season' (when food is scarce) or when crops are damaged by cyclones (Harvey et al. 2014).

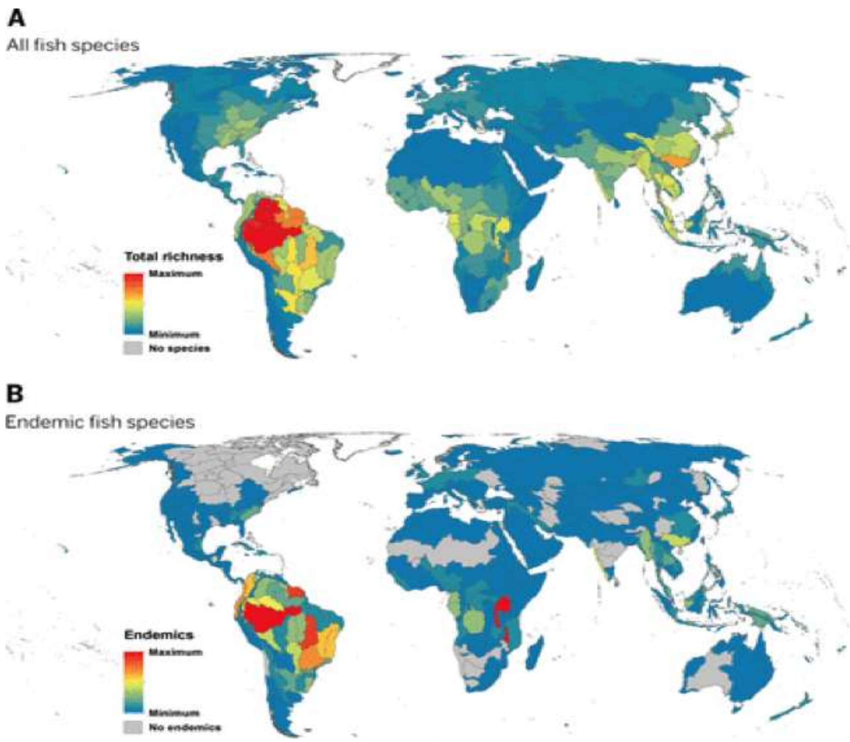
Wild meats, known as bushmeat, have high nutritional importance for many of the world's poor. The nutritional value and micronutrients tend to be much higher from meat than from plants, providing protein and fat, iron, zinc, and vitamin B-12 (Murphy and Allen 2003; Nasi, Taber, and Vliet 2011). A recent study from Madagascar shows that if children stopped eating bushmeat, anemia would increase by 29 percent (Golden et al. 2011). This study showed the importance of wild meat consumption, while also identifying that the bushmeat being consumed was from endangered lemurs. The conservation implications of bushmeat consumption are substantial, and in most of the world, the rates are unsustainable, leaving the rural poor permanently impoverished, while contributing to species extinctions (Bennett 2011; Brashares et al. 2011). There are also high risks having wildlife diseases transferred to humans, which then become emerging infectious diseases that are capable of causing pandemics (Karesh et al. 2012).

Bushmeat hunting to satisfy growing urban populations threatens wildlife species with extinction while eliminating protein sources for rural people – increasing their protein-energy malnutrition, stunted growth, and increased susceptibility to disease. It can also expose everyone along the trade route – from hunters, female traders, and urban consumers – to zoonotic diseases. Yet by decimating wildlife populations, it can also change the composition of forests (Brodie et al. 2009). What is safe to harvest in terms of human health, and what is safe to harvest for species survival, is a judgment that must be made at a specific site (Bennett et al. 2007). Unfortunately, demands of both the world's poor and urban elites in distant places are driving an unsustainable bushmeat trade that will have lasting effects on people, and on the ecological structure and function of tropical forests.

C. Forests, Freshwater, and Fisheries

Few people consider the important impact that forests have on freshwater systems, and the linkages with freshwater and coastal fisheries. But the ecosystem services that flow from tropical forests are critical to the health and productivity of streams, lakes and rivers, which in turn flow to coastal estuaries, deltas and mangroves. The high biodiversity and broad set of ecosystem services that forests provide are fundamental to the high biodiversity and productivity of tropical inland and coastal fisheries. For example, the Amazon basin has more species of freshwater fish than all marine fish found in the entire Atlantic Ocean. There is significant biodiversity associated with tropical inland fisheries. As shown in Figure 11, the richness of freshwater fishes, and endemism (species only found in one place), closely match the locations of tropical forests (Pimm et al. 2014). About 250 different species of fish are caught and used for food in Africa, Asia and Latin America.

Figure 8: Total richness (A) and endemic (B) freshwater fish species in the different freshwater ecoregions



Source: Pimm et al 2014

How important these ecosystem services are to inland and coastal fisheries has not been quantified, and most valuation studies only consider the local catch value of the fishery – a very narrow measure since it discounts commercial values (Barbier et al. 2011; Brummett, Beveridge, and Cowx 2013). Recent analyses indicate that the global value of inland captured fish (not aquaculture) was about $5.5 billion for 10.2 million metric tons in 2008 (likely a vast underestimate of up to 70 percent too low) (Brummett, Beveridge, and Cowx 2013).

As with many other ecosystem services, people pay attention when services become degraded or are lost (Barbier et al. 2011). Deforestation and dams can diminish stream quality leading to changes in water quality, quality, flows, temperature, and losses of biodiversity. Both change the variety of plants and leaf litter and flows throughout river systems, in turn affecting coastal and downstream forests, and the capacity of these areas to provide healthy fisheries.

Examples of food-related ecosystem services are found by looking at permanently or seasonally flooded forests, which include broad areas of the Amazon basin and much of the Mekong River Delta. For example, there were nearly 800,000 hectares of flooded forests that were inundated for 3-6 months of the year in the Mekong River Delta, but by the mid-1990s, the loss of flooded forest was paralleled by losses in fishery production (FAO 2011). These seasonally flooded forests act as a nursery and breeding ground for this highly productive fishery, so removing forests reduces fish. There are a multitude of water regulation services that flooded and riverine forests provide, but they also provide food (fruits and leaves) for fish. Places with more forest cover have fatter fish while sparser forests have smaller fish (Tanentzap et al. 2014).

The value of inland fisheries to meeting protein needs of the poor in tropical countries is huge, and often forms the highest share of animal protein (Welcomme et al. 2010; Barbier et al. 2011). The Great Tonle Sap area in Cambodia is the world's 4th most productive inland fishery, but it is highly dependent on the surrounding forests (Baran, Jantunen, and Chong 2007), and Cambodian people surrounding the lake rely on it: over 74 percent of people depend on agriculture and fisheries, with fish and inland aquatic animals (e.g. crabs) making up over 80 percent of animal protein in the Cambodian diet (Baran, Jantunen, and Chong 2007). Households consumed over half of what these fisheries produced, directly supporting their food security (FAO 2011). Fisheries are an important source of protein and micronutrients as well. For example, in much of Asia, small whole fish are eaten, providing an important source of calcium where other sources are lacking.

Recent studies are now looking at the value of ecosystem services, and river or lake functions, and the important role of small-scale fisheries for employment, for nutrition, or as a safety net. For example, inland fisheries in the upper Amazon region of eastern Peru are critical in helping forest dwellers deal with common shocks – such as family illness or major flooding. When forest people were faced with crises, they were more likely to turn to the river and fish as a safety net, than to try to extract more from forests (Coomes et al. 2010; Takasaki, Barham, and Coomes 2010). For both inland and coastal people, fishing often fills a transitory gap in food security (Hanazaki et al. 2013). Improving management of inland fisheries, which includes riverine forest protection, can have high economic importance to local residents. In Brazil, in a seasonally flooded area, better management and marketing of the pirarucú fishery between 1999 to 2006 led to 9-fold increase (from about 2200 to 20,650 individuals) in pirarucú fish, and harvest quotas increased 10-fold (from 120 to 1249 individuals). Between 1999 and 2006, the number of communities participating in management went from 4 to 108, and the annual incomes of participants doubled (Castello et al. 2009).

Coastal fisheries, many of which are highly dependent on mangrove systems, are highly important, and up to 80 percent of global fish catches depend on mangroves in some way (Ellison, 2008; Sullivan, 2005). For example, Malaysia's 567,000 ha of mangrove forests support over half of Malaysia's annual fish catch, totaling 1.28 million tons, directly and through ecosystem services that spillover to offshore fisheries (Chong 2007).

Mangroves are found in all 123 tropical and sub-tropical countries, but represent less than 0.5 percent of the world's forests (Alongi 2014) and globally, are being lost at a rate of 1 percent annually (FAO 2007), although the rate can be much higher in some places. Until the 1970s, most of the world's tropical coastline was covered with mangroves (Barbier et al. 2010), but over one-third of all mangroves have been destroyed since 1980 (FAO 2007) and many are on the verge of collapse. Mangroves provide a multitude of ecosystem services, and their role in providing breeding grounds and a nursery for fisheries is well understood. Most simply, the many tangled roots provide a safe place for small fish and crustaceans, limiting access by larger fish and other predators. When the fish are large enough, they leave mangroves in search of additional food, but have reached a size where they are less likely to be eaten. Mangroves also shelter small fish, buffering them from strong wave action. Mangroves also provide a strong supply of nutrients and food for the small fish they nurture, and also have a different temperature and salinity from other coastal areas, which can be important to the development of some species. The variety of foods that people receive from mangroves extend well beyond the species that they catch in the mangrove, given the important role of mangroves as nurseries for a wide variety of fish and other acquatic species (Barbier et al. 2011; Van Lavieren et al. 2012). Yet despite the ecosystem services that they provide to multiple sectors, mangroves are one of the most threatened types of tropical forest.

8. Forests and Human Health

Tropical forests:

- help control and reduce disease prevalence, and healthy and intact forests, for example, have less malaria and people get less diarrhea, than in disturbed areas.
- disturbance and deforestation mean that more people come in contact with diseases once limited to forests – so disease rates increase.
- disturbance and deforestation change how diseases spread– so diseases that might have stayed high in the forest canopy drop down to the forest floor, and are caught by species that then interact with humans.
- destruction increases the risks for emerging infectious diseases to turn into pandemic diseases, and Ebola, SARS, and H1N1 outbreaks are linked to wildlife and forest loss.
- hold a huge number of chemical compounds present in the multitude of species living in them, and many of these have important medicinal properties with high potential commercial value, or for billions of people relying on traditional medicines. Specific values of forest medicines are unknown, but the 2008 global value of traditional medicines was about US$ 83 billion dollars.
- remove pollutants from the air, providing health benefits on a localized scale.
- fires can lead to substantial economic losses at broad scales and also damage health, both at local and regional levels, contributing up to 10% of global air pollution.

Human health and ecosystems health are inextricably linked. Studies are beginning to show the myriad ways that different ecosystems, especially tropical forests, influence human health. These start with the vast importance of tropical forests for food and nutrition, and providing clean water, as previously discussed. But it is far broader than that, and benefits include medicinal plants from forests, protection from infectious diseases, and the avoided health impacts from burned forests. We are only just beginning to understand the complex and adverse impacts on people (particularly poor people in developing countries) as ecosystems lose their ability to provide goods and services supporting human welfare. For example, Myers et al. (2013) note that the huge conversion of ecosystems, what they call an "ecological transition," has benefitted people who could capture the health, infrastructure, and market benefits from this transition. But many poor people, especially rural poor, are more vulnerable given ecosystem degradation, and they are unable to afford or access substitutes, or benefit from infrastructure such as potable water systems.

A. Control and Avoidance of Disease

There is a robust debate on if, when, and how biodiversity helps control and reduce the prevalence of disease. Since tropical rainforests are among the most biodiverse systems in the world, it could be expected that biodiversity would help limit disease exposure and transmission (Keesing et al. 2010; Wood et al. 2014). The evidence for these emerging and debated findings is based on places where habitat has been converted and biodiversity has been lost. This link between habitat conversion and malaria was known as "frontier malaria" given its prevalence among colonists clearing forests (Sawyer 1988).

There are many ecological reasons for why habitat transformation and deforestation affect disease incidence and transmission. For malaria, for example, intact forests have high numbers of predators that eat mosquitoes and the cooler temperatures in forests slow the rate at which mosquitos mature, compared to disturbed areas (Vittor et al. 2009). Generally, species carrying diseases have fewer competitors or predators in places with less biodiversity. Second, there are more things to bite, reducing the risk that humans will be bitten and infected. With more creatures being bitten, there is less chance that all of them will be reservoirs or hosts to malaria or other diseases – which dilutes the overall effect of the disease. This "dilution effect hypothesis" has found significant support in field-based studies, but is still debated in the literature on disease (Myers et al. 2013; Wood et al. 2014). Deforestation improves the conditions for malaria, with small pools of standing water for larvae and warmer temperatures – which means more breeding area and faster larval growth.

Studies from the Brazilian Amazon show that compared to intact forests, disturbed areas had high increases of one type of mosquito that causes malaria (Laporta 2013), with roads, forest fires, and selective logging all acting as risk factors for increased malaria (Hahn et al. 2014). Even small (4.3 percent) increases in deforestation led to huge (48 percent) increases in malaria incidence in one area in Brazil. Similar results have also been found for Africa (Cohuet et al. 2004; Guerra, Snow, and Hay 2006; Munga et al. 2006) with one study suggesting a 1 percent reduction in forest cover leads to an 8 percent increase in malarial mosquitoes (Hawkins 2010). Malaria transmission in Asia is more complex, but is linked to deforestation in some places (Guerra, Snow, and Hay 2006; Wayant et al. 2010). In Indonesia, places with more protected primary forest had lower rates of child malaria, while places with more secondary (disturbed) forest cover had more child malaria (Pattanayak et al. 2005). A study of a protected area in Indonesia shows how tropical forest hydrological services, the clean water that flows into streams, helps reduce diarrhea in downstream populations (Pattanayak and Wendland 2007).

Ample evidence shows that deforestation is also linked to changes in other disease vectors and hosts. Deforestation has a been linked to outbreaks of schistosomiasis, west nile fever, hantaviruses, simian immunodeficiency virus (SIV), leishmaniasis and others (Wilcox and Ellis 2006; Campbell et al. 2011; Laporta et al. 2013; Myers et al. 2013). Deforestation is blamed for the 2014 Ebola outbreak in West Africa (McCoy 2014; West and McDonnell 2014), and in Kenya, has been linked to Ebola, Rift Valley Fever (RVF) virus, dengue fever virus and West Nile Fever Virus (Sang and Dunster 2001). While there are different mechanisms for each disease, human movement into forests often changes disease pathways and vectors, as well as exposing people to diseases that they had little contact with until they entered or disturbed forests. For example, while yellow fever may be endemic to forests, it can drop from the forest canopy to the forest floor when trees hosting monkeys and mosquitoes are cut.

Human consumption and trade of forest animals, especially with deeper and deeper encroachment into forests, has been linked to a high number of emerging infectious diseases that come from wildlife (these are known as zoonotic diseases) and have been linked to the spread of HIV/AIDs, severe acute respiratory syndrome (SARS), Ebola and other hemorrhagic fevers, Nipah virus, avian influenza, pandemic H1N1, and MRSA (Keesing et al. 2010; Campbell et al. 2011; Cascio et al. 2011; Morse et al. 2012; Rabinowitz and Conti 2013). Estimates of emerging infectious diseases suggest that between 60 percent to 80 percent are zoonotic in origin, with the greatest probabilities of new diseases coming from the tropics (Woolhouse and Gowtage-Sequeria 2006; Woolhouse et al. 2012; Jones et al. 2013; Morens and Fauci 2013).

Ample evidence shows that climate change is already exacerbating most of the disease transmission pathways and vectors, since warmer climates extend the area that species can use (e.g. more mosquitoes are now moving into higher elevation areas that are warmer) and extend their overall range (winters aren't as cold and no longer reduce levels of die-off) (Rohr et al. 2011; Grace et al. 2012; Jones et al. 2013; Myers et al. 2013). Other climate change impacts, such as increases in rainfall or flooding (leading to standing water), will lead to increases in disease carried by mosquitoes. There are a myriad of other potential effects on disease transmission from the loss of tropical forests. While the magnitude and the exact diseases and their spread are subject to debate, there is agreement that climate change and deforestation links increase the probability of major global pandemics.

B. Tropical Forests and Medicines

Tropical forests have among the highest biodiversity in the world, so it should not be surprising that there are a huge number of different chemical properties that exist for different functions. There are a wide range of different mechanisms that plants and animals have: there are chemicals to attract other insects or pollinators, poisons to keep predators away, and chemicals that are equivalent to coagulants in blood to stop sap from leaking if plants are eaten. Some rainforest frogs, such as poison dart frogs, produce powerful neurotoxins, while other plants and animals produce fungicides and antibiotics, and salamanders can regenerate their limbs.

It is remarkable how many chemical compounds have evolved along with species diversity. For example, different species of venomous snake produce different venoms and different plant species have chemicals to attract or repel animals (Gertsch 2009). Research is identifying the best prospects for new drug compounds, of great consequence to pharmaceutical companies (Gertsch 2009; Albuquerque, Ramos, and Melo 2012).

Medicines are derived from wild plant and animal medicines through several pathways. First, there are directly used products. Then, there are modern pharmaceuticals that are created from wild plants and animals. Finally, there are modern pharmaceuticals that are synthesized based on the molecular properties of wild species without directly using them (Robinson and Zhang 2011; Newman and Cragg 2012).

Forest dwelling people have made use of some of these species and compounds traditionally. While the exact number of people in forested areas using wild species for medicine is unknown, numbers are likely high, since 70–95 percent of people living in developing countries (3.5 to 4 billion people) rely chiefly on traditional medicines for their primary healthcare needs (Robinson and Zhang 2011). One estimate suggests that globally, 53,000 different plant species (not necessarily from forests), are used medicinally (Hamilton 2004). Even apes use of wild plants for medicinal purposes. Scientists studying Ugandan chimpanzees wondered why they ate plants with a low nutritive value, until they found that some of these plants help protect the chimps from parasites (Krief 2012). There is some evidence that places with higher diversity have a higher number of species used. For example, India is a high biodiversity country, with a long tradition of using medicinal species. Of the 17,000 plants in India, 7,500 have been used for traditional medicines (Senthilkumar, Murugesan, et al. 2012). In Brazil, there is also a high diversity of animal species (354), with little overlap between those used medicinally (197), and those valued as food (154) (Alves and Rosa 2007). In Madagascar, just one relatively small rainforest watershed, the Makira Protected Area, had 241 plants used locally as medicines (Golden et al. 2012).

The emerging "ecological transition theory" (Myers et al. 2013) suggests that people with access to modern medicine and health infrastructure make use of that, but people with no access rely on a wide range of natural products. Less wealthy and less educated communities in Kalimantan (Indonesian Borneo) used more species medicinally than wealthier or more educated communities (Sheil and Salim 2012). The majority (94.2 percent) of the 140,000 poor people living in the Makira Protected Area (Madagascar) use traditional medicines weekly (Golden et al. 2012). To give some context of the value is of this "free" medicine, it would be roughly equivalent to a family in the USA spending up to 63 percent of their household income for medicine (Golden et al. 2012). This shows the huge, and free, benefit that poor tropical residents derive from a range of different species.

The value of traditional medicines is hard to estimate, and is likely to be underestimated. The global value in 2008 was calculated to be worth US$ 83 billion (Robinson and Zhang 2011). Yet this number would be much larger if it included the contributions of forest-based plants and animals to modern medicine and pharmaceuticals, since one-quarter of all modern medicine is derived either directly or indirectly from medicinal plants, or from synthesizing new compounds based on traditional use of plants (Robinson and Zhang 2011). Furthermore, a study of cancer drugs approved in the USA from 1940 to 2010 found that 48.6 percent were either natural products or derived from natural products. This gives some idea of the potential medical importance of conserving the places with highest plant and animal diversity in the world (Newman and Cragg 2012).

C. Forest Fires in the Tropics and the Health Impacts of Air Pollution

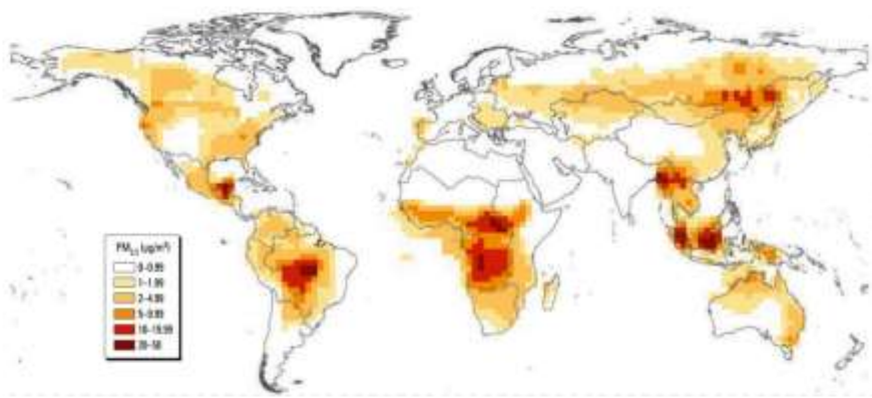
The degradation and loss of forests has a direct impact on air quality and human health, particularly when forests are cleared by burning. Vegetative fires release significant amounts of carbon-containing trace gases (e.g., CO and CH_4), nitrogen-containing compounds (e.g., NO_x), sulfur-containing compounds (e.g., SO_2), and halogen-containing compounds (e.g., CH_3Cl) due to incomplete combustion. CO, volatile organic compounds, and NO_x react in the presence of light to create tropospheric ozone (see Langmann et al. 2009). Vegetative fires are also a source of heavy metals in the atmosphere. Yamasoe and coauthors (2000) estimate that the burning of savanna and tropical forest biomass produce about 1 million tons of copper and 3 million tons of zinc per year in the atmosphere, about 2-3 percent of the global budget of these trace species. In Brunei Darussalam, researchers have detected a number of known and suspected carcinogens (e.g. benzene, toluene, ethylbenzene, xylene, and phenol) in the smoke plumes of local forest fires (Muraleedharan et al. 2000). On-site laboratory tests of biomass burning in the Amazonian forest measured emissions of ultrafine particles ($PM_{2.5}$) ranging from 60 to 400,000 $\mu g/m^3$ (Costa et al. 2012). (The healthy 24-hour mean exposure limit recommended by the WHO is 25 $\mu g/m^3$.) These ultrafine particulates are especially damaging to human health because they may be inhaled deep into the lungs.

Tropical forest fires affect more than just air quality in the immediate area. In some parts of the world, such as Southeast Asia, they frequently contribute to regional air pollution. In 2013, out-of-control fires from land clearing in the Indonesian provinces of Kalimantan and Sumatra combined with dry weather conditions caused one of the worst haze episodes in Malaysia and Singapore in recent history.[12] During a previous episode in 1997, researchers documented a marked increase in hospitalizations for people suffering from cardiorespiratory problems (Mott et al. 2005). Some pollutants may even be transported thousands of kilometers beyond the region. For example, emissions from fires burning in South America raised concentrations of CO over Australia (Gloudemans et al. 2006 cited in Langmann et al. 2009).

Globally, Jacobson found that 5 to 10 percent of worldwide air pollution mortalities were due to biomass burning, or an average of 250,000 people each year (Jacobson 2014). Johnston and coauthors (2012) estimate that landscape fires were responsible for 339,000 deaths each year globally between 1997 and 2007 due to illnesses associated with $PM_{2.5}$ exposure. The tropics of sub-Saharan Africa and Southeast Asia are the worst affected regions, with 157,000 and 110,000 deaths each year respectively (figure 12 below). Mortality due to air pollution from fires was highest during the El Niño year of 1997-1998 due to drier-than-normal conditions, with an estimated 532,000 deaths. This modeled increase in mortality suggests the intricate connection between forests, fires, air quality, and human health. Continued forest degradation combined with the projected drying effects of climate change in some regions such as Amazonia and shifts in regional weather patterns could have important implications for exposure to air pollution.

[12] http://uk.reuters.com/article/2014/06/18/us-indonesia-haze-idUKKBN0ET0H320140618.

Figure 9: Annual average PM2.5 concentrations attributable to landscape fires, 1997-2006



Source: Johnston et al. 2012

Apart from fires, tropical forests influence local air quality in other complex ways due to their role in local and global cycles of energy and materials. A scenario in which climate change leads to the dieback of Amazon forest could affect regional air quality by reducing precipitation and raising the amount of dust in the atmosphere. Changes in vegetative cover could also affect regional air quality through altered biogenic emissions of volatile organic compounds such as isoprene, which can either create or destroy ozone (Betts, Sanderson, and Woodward 2008). In unpolluted regions, where levels of NO_x are low, tropospheric ozone would decrease; in polluted regions, they would increase, harming both plants and people.

9. Deforestation, Biodiversity Loss, and Lost Ecosystem Services

Tropical forests:

- rate of loss increased from 2000 to 2012, with the greatest losses in Brazilian rainforests, Asia-Pacific rainforests, and Africa's moist forests.
- are fragmented, and relatively few large intact areas of forest remain. The biggest blocks left are in the Amazon, Congo Basin, and Indonesia.
- experience disturbance as part of natural cycles – but human impacts far exceed anything natural. More disturbance means less healthy forests and reduced ecosystem services.
- with higher biodiversity are healthier and high biodiversity is a form of biological insurance. These forests have greater resilience – they have a better capacity to rebound from stresses.
- deliver ecosystem services even when disturbed. However, impacts aren't immediately seen, so we may be vastly underestimating human impacts.
- that are undisturbed, intact, and healthy provide vastly higher ecosystem services than forests that have been cleared and regrown or than plantation forests.
- healthier is higher when they are in large blocks than small patches of forest, that lose many of their species, and ecological value, over time.

Globally, the rate of tropical forest loss increased from 2000 to 2012. The most severe losses were of tropical forest were experienced in the Brazil (360,277km^2 or 4 percent of total land area), Indonesia (157,850 km^2 or 9 percent of total land area), and the Democratic Republic of Congo (58,963 km^2 or 3 percent of total land area) (Hansen et al 2013, see figure [13] below), though the annual rate of forest loss in Brazil has declined.[13] Land use change is the main driving force affecting ecosystems, causing the loss of biological diversity and reducing the supply of ecosystem services (MEA 2005).

[13] These figures are for gross loss and are not netted of the area of forest gain.

Figure 10: Areas of intact forest in 2000 *(green)* and forest loss from 2000-2012 *(pink)*

Sources: Global Forest Watch (www.globalforestwatch.org) with underlying data on intact forest landscape from Potapov et al (2008) and data on forest loss from Hansen et al, 2013.
Note: "intact" forests are large, unbroken areas of forest at least 50,000 hectares in size and 10 km in width, which "show no signs of significant human activity and are large enough that all native biodiversity, including viable populations of wide-ranging species, could be maintained" (see Potapov et al 2008).

Scientists have been unable to perfectly predict "how much" biodiversity, intactness, or ecosystem health can be lost before the ecosystem services provided by forests collapse. Any different type or level of use will have an impact – but that impact may be different even in the same place at a different time of year (e.g. if it affects breeding or nesting seasons). Changes in ecosystems aren't linear, and abrupt changes are possible both across time and space. For example, there is a time lag between habitat losses that are sufficient to cause extinction and when extinctions actually happen. Long term data for a fragmented cloud forest in Colombia shows that there were 128 bird species in 1911, 104 by 1959, and only 88 by 1992 (Kattan, Alvarez-López, and Giraldo 1994). Species that live for a long time may remain in what are apparently viable numbers, but may not be successfully reproducing. While disturbances, such as fires or storms, are a natural part of the cycle that shapes ecosystems, human impacts are happening on a broader scale. The complexity of understanding ecosystem service delivery has to do with both their complexity and geographic and temporal scales.

Seemingly small acts can have large consequences throughout a broad system – as evidenced by what happens when predators are eliminated. Large predators are often called keystone species – because their actions regulate populations of numerous small species they prey upon. If predators are wiped out from a system, populations of smaller mammals can rise dramatically, and these herbivores will eat the seeds and saplings that grow into a mature forest (Terborgh et al. 2001). For example, in many Latin American (neotropical) forests, small rodents called agoutis act like temperate squirrels, collecting and burying seeds widely throughout the forest. But if predators are eliminated, agouti numbers rise and most seeds are eaten rather than buried. Over time, the agouti population will stabilize. But none of the trees preferred by agoutis will grow since seeds have been eaten, and the entire composition of the forest will change, reducing (for a long time) the delivery of ecosystem services.

There is emerging evidence that higher diversity acts as a form of biological insurance – helping ecosystem stability and resilience, the ability of ecosystems to withstand, reorganize and rebound after a shock (Laliberte et al. 2010; Mayfield et al. 2010). Higher biodiversity is also linked to higher ecosystem function and service provision (Flynn et al. 2011; Cardinale et al. 2012), and reduced biodiversity leads to reduced ecosystem services. For example, removing just one of many species of fish from a tropical river can worsen freshwater quality (Taylor, Flecker, and Hall 2006), and a recent study from Madagascar shows the links between higher diversity and ecosystem services, and degradation, lower diversity, and lower ecosystem service provision (Brown et al. 2013). A study comparing 2,220 primary and undisturbed forests with high biodiversity, and disturbed and degraded forests showed that there was an "overwhelmingly detrimental effect on tropical biodiversity" (Gibson et al. 2011). Forest fragments had both fewer species and fewer groups of species performing similar functions than intact areas (Ahumada et al. 2011).

Patches of forest surrounded by other uses rarely remain healthy, since plant and animal populations drop, and over time, have a smaller gene pool and less success in reproducing. Over time, the entire structure and composition of the plants and animals within a fragment changes, and the chances for extinction increase. Even tropical forests with a high degree of protection are feeling the impacts of environmental changes and disruptions nearby but outside their boundaries, demonstrating strong ecological connections (Laurance et al. 2011). Researchers have found that primary forests are "irreplaceable for sustaining tropical biodiversity" (Gibson et al 2011: 381) and offer the highest service values. In short, tropical forest degradation, loss, or conversion can reduce biodiversity, which can significantly reduce or eliminate the flow of ecosystem services.

10. Conclusion

There has been an explosion of science on the myriad of ways that tropical forests influence all facets of our lives—wherever in the world we live. From the teleconnections of global weather systems, to the foods we eat, to the potential for pandemic diseases or cures for cancer – tropical forests, their products, and services profoundly and disproportionately affect our lives. While tropical forests make up less than 5 percent of the Earth's land surface, they are the terrestrial ecosystem with the highest level of ecosystem services.

Virtually all tropical forests and the species within them are threatened, whether from local clearing for food and feed, for large industrial plantations, or from climate change (which is already stressing forests worldwide). When the size and health of forests decline, so too do the variety of services that they provide, both near and far. Much of the science on tropical forests is well established, and new connections between tropical forests and ecosystem services are emerging quickly. Yet all of the science points to the need for rapid actions to manage and protect remaining tropical forests and the species within them. This is imperative if we want to insure a lasting flow of ecosystem services. Some key elements of best practices for tropical forest management to insure lasting ecosystem services are:

- **Bigger is better**: larger blocks of forest areas are healthier, less vulnerable to many threats, and larger populations of species encourage genetic diversity.
- **Redundancy is good**: multiple blocks of tropical forest should be protected to minimize risk from shocks (e.g. disease, natural hazard, famine).
- **Connectivity is key**: maintaining or re-establishing connectivity in 'ecological corridors' between different forest areas, and different ecological systems should be encouraged whenever possible. Protecting coastal to inland forests may be highly prudent to insure inland rainfall, and lowland to highland forest connectivity so species can move to cooler areas with climate change.
- **Threatened areas or species should get priority:** Tropical forests containing critical habitats, which are places with irreplaceable and/or vulnerable species and habitats, and species of global and national importance, should have priority for conservation. Cloud forests, riverine forests, dry forests, and mangroves are highly threatened and should have highest priority.
- **Diversity is best:** Large blocks of tropical forest with high biodiversity should be priorities for conservation, especially when areas can span diverse types of forests, going from cloud to coastal forests.
- **Representation is essential:** each type of tropical forest should be included within multiple conservation areas, both within each country and in different countries.
- **Protect climate refugia and future needs given climate change:** climate change will affect forests, pushing species to new areas, so there is a need to protect forests where

movements will likely occur in the future, and the places that were key to supporting species in the past (climate refugia).

- **Support and protect evolutionary potential:** Identify tropical forests that are especially important for evolutionary processes and diversity, such as evolutionarily distinct species.
- **Sooner is better:** Protecting and managing forests is always cheaper than restoring them, and the costs of conservation action generally increase with time.
- **Reduce threats:** there is a need to both reduce existing threats, but also to model new and emerging threats, both direct and direct, from all sources, including from climate change.
- **Use the precautionary principle:** not all species or forests are fundamental to delivering ecosystem services, but our knowledge and understanding of interactions is very low. There are many examples of species that went extinct that may have held the cure for ulcers, or cancer, or a plant with a key gene for drought resistance.
- **Mainstream biodiversity and ecosystem management as part of functional landscapes**, asking "How can healthy ecosystems and processes better support this landscape now and in the future?" This means protecting forests near agricultural fields to support rainfall and pollination, or identifying what forest areas are needed to insure regional rainfall patterns remain intact, or which forests are critical in protecting water quality and for energy or fisheries.

Taken together, these actions would begin to protect the variety of ecosystem services provided by tropical forests. Our understanding of the *science* underpinning the variety, timing, and magnitude of ecosystem services from tropical forests continues to improve dramatically, and each new finding generally shows that we have underestimated their importance. And if we underestimate the variety, timing, magnitude or reach of services—that means that we underestimate the *value* of the services forests provide. For example, tropical forests are pivotal in influencing global weather patterns, so protecting Amazonian forests may be necessary to insure that summer rain falls in the Midwestern United Sates. What seems clear is that our estimates and valuation have understated the importance of tropical forests. As demonstrated in this paper, the values provided by tropical forests are immense, widely distributed across the globe, and of vital importance to many economic sectors. Urgent protection of remaining tropical forests and the species within them, especially given climate change, should thus be a global priority.

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