Why Maintaining Tropical Forests Is Essential and Urgent for a Stable Climate

Rosa C. Goodman and Martin Herold

Abstract

Tropical forests have the highest carbon density and cover more land area than forests in any other biome. They also serve a vital role as a natural buffer to climate change —capturing 2.2–2.7 Gt of carbon per year. Unfortunately, tropical forests, mangroves, and peatlands are also subjected to the highest levels of deforestation and account for nearly all net emissions from Forestry and Other Land Use (FOLU) (1.1–1.4 Gt C / year). Net emissions from FOLU accounted for only 11% of total anthropogenic greenhouse gas emissions or 14% of total carbon emissions in 2010, though these figures are somewhat misleading and do not reflect the full potential of tropical forests to mitigate climate change. First, net FOLU emissions have reduced only slightly while emissions from all other sectors have skyrocketed. Secondly, the FOLU net flux is made up of two larger fluxes —deforestation emissions (2.6–2.8 Gt C / year) minus sequestration from forest regrowth (1.2–1.7 Gt C / year). Additionally, intact tropical forests also appear to be capturing at least 1.0 Gt C/ year. Gross deforestation, therefore, accounts for over a quarter of all carbon emissions, and tropical forests have removed 22–26% of all anthropogenic carbon emissions in the 2000s. If deforestation were halted entirely, forests were allowed to regrow, and mature forests were left undisturbed, tropical forests alone could have captured 25–35% of all other anthropogenic carbon emissions. On the other hand, if climate change continues unabated, forests could turn from net sinks to net sources of carbon. Forest-related activities are among the most economically feasible and cost-effective mitigation strategies, which are important for both short- and long-term mitigation strategies. Action is needed immediately to utilize these natural mitigation solutions, and we need coordinated and comprehensive forest-related policies for mitigation. An international mechanism such as REDD+ is essential to realize the great natural potential for tropical forests to stabilize the climate.

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Why Maintaining Tropical Forests Is Essential and Urgent for a Stable Climate

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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, "Why Maintaining Tropical Forests is Essential and Urgent for a Stable Climate" by Rosa C. Goodman and Martin Herold, was commissioned by CGD to summarize the state of the science of the relationship between forests and climate change. It is designed to assist the non-scientist to understand the role played by forests in the global carbon cycle and the significance of greenhouse gas emissions from tropical deforestation in particular. The paper provides answers to frequently asked questions, such as "Why focus on the tropics?" and "Why don't we just plant more trees?"

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Executive Summary

Forests, climate, climate change, and climate change mitigation are inextricably linked. Natural systems cycle enormous amounts of carbon and, if treated appropriately, could be utilized to remove anthropogenic emissions from the atmosphere. On land, annual carbon fluxes are dominated by forests, which could become either a large source of carbon dioxide (CO_2) emissions or a substantial part of the mitigation solution, depending on how we treat them on an international level and manage them locally. Terrestrial ecosystems have played an important role in mitigating climate change thus far, removing over 4 gigatons of carbon (Gt C) from the atmosphere each year. Over two-thirds of this sink is due to tropical forests alone: mature and regrowing tropical forests are capturing 2.2–2.7 Gt C / year. Tropical forests have the highest carbon densities in the world and store over 470 Gt C.

Unfortunately, tropical forests are also subjected to the highest levels of deforestation and therefore account for nearly all net emissions from forestry and other land use (FOLU; 1.1–1.4 Gt C / year). Considerable amounts of carbon are released when forests are cleared and burnt, and yet more greenhouse gases are emitted from the subsequent land uses, such as agriculture. Draining, burning, and degrading peatlands is especially detrimental, releasing large quantities of CO_2 and other more powerful greenhouse gases. Industrial agriculture and commercial logging are the main drivers of deforestation and degradation in South America and Southeast Asia, the major hotspots for forest-related emissions.

The proportion of total emissions from net FOLU has gone down since the 1990s, making up only 11 % of total anthropogenic greenhouse gas emissions (CO_2-equivalents) in 2010. However, this figure is somewhat misleading because (i) net FOLU emissions have reduced only slightly while emissions from all other sectors have skyrocketed in recent years, (ii) the net land flux (1.1–1.4 Gt C/ year) is made up of two separate, larger fluxes: deforestation emissions (2.6–2.8 Gt C / year) minus sequestration from forest regrowth (1.2–1.7 Gt C / year), and thus (iii) the proportion of total greenhouse gases nor the net flux reflect full role of tropical forests in the carbon cycle or the large potential for forests to mitigate climate change. If gross fluxes are considered separately, gross FOLU emissions account for over a quarter of all carbon emissions, and tropical forest regrowth captured 12–16 % of all anthropogenic carbon emissions during the 2000s. If sequestration in mature forests (~1.0 Gt C/ year) is included in the tropical forest sink, tropical forests have removed 22–26 % of all anthropogenic carbon emissions in the 2000s. Thus, if deforestation were halted entirely, forests were allowed to regrow, and mature forests were left undisturbed and continue to net carbon sinks, tropical forests alone could capture over a quarter of all other anthropogenic carbon emissions (30–35 % compared to emissions levels in the early 2000s or 25–30 % compared to carbon emissions in 2010). Finally, very recent data shows that tropical deforestation may be increasing again.

Compared to other mitigation strategies, forest-related activities, especially reducing emissions from tropical deforestation, are among the most economically feasible and cost-effective options and the most viable strategy in the land sector. Reducing CO_2 emissions from forestry plays a relatively large role in reducing total CO_2 emissions in the short term and buys us time to develop other mitigation and adaptation strategies. Unlike experimental carbon dioxide removal technologies, trees (planted or left undisturbed) can and already do remove carbon from the atmosphere naturally, which is essential for meeting long-term climate targets.

Action is needed immediately, especially if we are to utilize this large and natural mitigation option. Delaying action only puts more pressure on drastic changes in the future, lessens our overall chances of avoiding dangerous climatic changes, and may eliminate many of the options available to use today (such as forestry). Forests themselves are threatened by climate change and could eventually turn from net sinks to sources of CO_2 if climate change continues unabated. For effective climate change mitigation, we need coordinated and comprehensive mitigation policies among regions and land management activities. Drivers of forest-related emissions and the mitigation potential of forestry activities vary by region, and interventions should be planned accordingly. Over the past decade, the reduction in deforestation in Brazil and rise in afforestation in China emphasize the potential for national policies to improve land management, reduce carbon emissions, and enhance sequestration. Many countries are already engaging in REDD+ (Reducing Emissions from Deforestation and forest Degradation), and it is important to keep this momentum going. An international mechanism such as REDD+ is needed to realize the great natural potential for tropical forests to stabilize the climate.

This report synthesizes a large number of technical publications to summarize the role of tropical forests in climate change mitigation and, thus, forms the scientific basis for the need to maintain and manage tropical forests wisely.

1. Introduction

1.1 Relevance and importance to the development community

Climate change is a huge and imminent threat to society, and people in developing countries may be the most vulnerable to its effects (Field et al. 2014). Tropical forests are vastly important for society: supplying timber and non-timber forest products, supporting local livelihoods, and providing valuable ecosystem services. These forests also play an important role in both land use change emissions and immediate climate change mitigation action. The mechanisms proposed to do so, such as REDD+ (Reducing Emissions from Deforestation and forest Degradation), will need to focus interventions on addressing the direct and indirect drivers of deforestation and degradation, which brings up many social, economic, and development issues. Funds can potentially be used to build synergies between forest conservation and poverty reduction (Wunder 2001), but 'safeguards' will need to be upheld to ensure that any climate change mitigation activities promote social and environmental benefits. This chapter, however, will focus on the scientific basis for the need to maintain and manage tropical forests. Our intention is to synthesize a vast number of technical publications into a concise and accessible report.

1.2 Relevance and importance for policy-makers

Mitigation is defined as 'a human intervention to reduce the sources or enhance the sinks of greenhouse gases' (Edenhofer et al. 2014). Forest-related interventions, especially reducing deforestation, are cost-effective and vitally important for immediate climate change mitigation action. Afforestation and forest restoration also safely sequester carbon from the atmosphere, which is a necessary component in achieving long-term climate goals. Forest related activities are economically viable (Stern 2006), moderately easy to implement, and immediately available to us to act on climate change mitigation (no new or risky technology) (Smith et al. 2014).

Meeting a target of limiting a mean global temperature rise to 2 °C over pre-industrial levels —a number agreed upon in the 2010 Cancun agreements— is technically possible, but the political will is lacking (UNEP 2013). This makes meeting emissions targets more difficult and puts us all at risk of the effects of catastrophic climate change. The United Nations Environment Programme warns that this slow and weak political resolve will be costly — causing countries to undertake more drastic, expensive, difficult, and risky routes to reduce emissions by 2020 (UNEP 2013). Later-action scenarios are more risky: delaying action results in (i) higher accumulation of greenhouse gases (GHGs) in the atmosphere, (ii) higher risk of overshooting GHG concentrations and global temperature increases, (iii) greater near-term impacts of climate change, (iv) fewer options to mitigate climate change in the future (such as many forest-related options), and (v) greater dependence on achieving a net sink in greenhouse gases within a few decades (and the technologies required for negative emissions may have severe negative impacts) (UNEP 2013).

There is a large 'gap' between emissions reductions expected from current national pledges and commitments and the emissions reductions needed to meet climate targets, but forestry has a large potential to fill this gap. Implementing current pledges and commitments are estimated to lower emissions by only 3–7 Gt CO_2eq / year, leaving an 'emissions gap' in 2020 of 8–12 Gt CO_2eq / year for a 2 °C target (assuming least-cost scenarios) and 2–5 Gt CO_2eq / year more with a more strict 1.5 °C target that some groups of countries are calling for (UNEP 2013). International cooperative agreements, such as REDD+, are key in closing this 'emissions gap' (UNEP 2013). Of all international cooperative initiatives, reducing deforestation is estimated to have the highest maximum potential to reduce greenhouse gas emissions —up to 25 % or 4.3 Gt CO_2eq / year in 2020 (UNEP 2013).

Thus, given the severe negative consequences of delaying climate change mitigation action and the multiple benefits of conserving and maintaining forests effectively, it is sensible to act immediately to reduce tropical deforestation and enhance sequestration and to utilize the REDD+ mechanism to do so. Throughout this chapter, we will summarize the current science to make the case for the physical benefits of maintaining and managing tropical forests.

1.3 Summary of carbon emissions and reservoirs

Our current understanding of the historic carbon cycle accounts for both emissions into the atmosphere (sources) and removals from the atmosphere (sinks), though there is some uncertainty, especially regarding the land use flux and residual land sink. Before the industrial revolution, deforestation totaled 7.5–9 million km^2 worldwide (Ramankutty and Foley 1999, Goldewijk 2001) and released approximately 27 Gt C (Pongratz et al. 2009) (summarized in Ciais et al. 2013). Since then, net emissions from land use change (deforestation minus forest regrowth) have totaled 180 ± 80 Gt C, and emissions from fossil fuels combustion and cement production have totaled 375 ± 30 Gt C (Ciais et al. 2013). Thus, of the 555 ± 85 Gt C emitted by humans between 1750 and 2011, one third has been from net land-use change. Fortunately, only 240 ± 10 Gt C have remained in the atmosphere because natural sinks in the global carbon cycle have removed over half of total emissions from the atmosphere. The oceans have stored an additional 155 ± 30

Gt C and the land, mostly forests, has gained 160 ± 90 Gt C (Figure 1). Excess carbon dioxide is dangerous both in the atmosphere, where it has a greenhouse effect and causes warming, and in the oceans, where it causes acidification. Of the three reservoirs, the terrestrial sink is the only safe reservoir for excess carbon, where it accumulates in plant tissues and eventually the soil.

It is also important to note the total carbon stored in each reservoir, which both put the global carbon cycle into perspective and have the potential to be released. The atmospheric reservoir has increased from 589 to 829 Gt C since the industrial revolution, thus reaching a carbon dioxide concentration of over 390 ppm by 2011. Living terrestrial vegetation stores 420–620 Gt C (more than half of this in tropical forests), and dead plant material in litter and soils holds 1,500–2,400 Gt C, not including wetlands (300 to 700 Gt C) or permafrost (~1,700 Gt C) (Ciais et al. 2013). Up to 1,575 Gt C remain stored in gas, coal, and oil. Oceans have by far the largest stores of carbon in the surface, intermediate, and deep sea, dissolved organic carbon, marine biota, and ocean floor sediments (>40,000 Gt C; Figure 1).

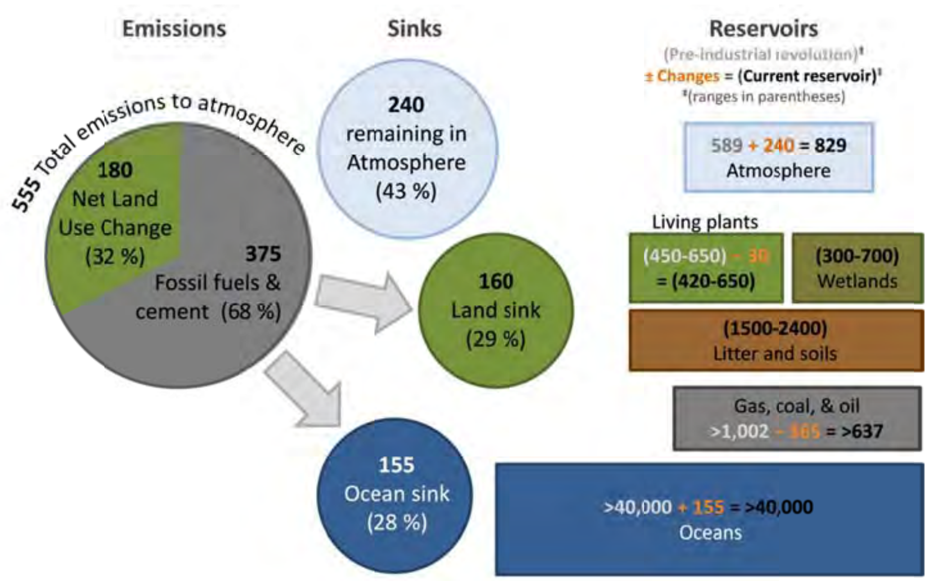

Figure 1. Diagram of cumulative carbon emissions and reservoirs. Note that net land use change emissions are gross emissions minus carbon captured by regenerating forests, and the land sink is additional sequestration. Units are in Gt C. Small circles represent changes (i.e., sinks) from 1750 to 2011 (anthropogenic emissions and natural sinks), and rectangles show current reservoirs (original +/- changes since 1750). Explanation of reservoirs (right) are given in the figure. Data from Table 6.1 and Figure 6.1 in Ciais et al. (2013).

Box 1. Terms and units explained

C, CO_2, and CO_2eq

We often express carbon in terms of elemental carbon (C), but carbon dioxide (CO_2) is what we emit and what accumulates in the atmosphere. The two can be converted as follows:

1 unit C = 44.01/12.01 units CO_2, so 1 t C = 3.66 t CO_2.

Other greenhouse gases (GHGs) have different potencies in their ability to cause warming. Thus, they are often reported as 'CO_2 equivalents' (CO_2e or CO_2eq) as a simplified way to show their global warming potential relative to that of CO_2. For example, one tonne of nitrous oxide is 310 times more potent than one tonne CO_2 in the atmosphere. The CO_2-equivalents below are based on the 100-year global warming potentials from the IPCC Second Assessment Report (Schimel et al. 1996):

Carbon dioxide (CO_2): 1
Methane (CH_4): 21
Nitrous oxide (N_2O): 310
Hydrochlorofluorocarbons (HCFCs): 90–1,500
Chlorofluorocarbons (CFCs): 3,800–8,100
Fluorocarbons, perfluorocarbons (PFCs): 6,500–9,200
Hydrofluorocarbons (HFCs): 140–11,700
Sulfur hexafluoride (SF6): 23,900

Basic units

Basic mass and area units are summarized below:

1 t (metric tonne) = 1000 kg (kilogram) = 1,000,000 g (gram) = 1 Mg (Megagram)
1 Gt (gigatonne) = 1 billion (10^9) tonnes = 10^{15} g = 1 Pg (petagram)
1 ha (hectare) = 100 m × 100 m = 10,000 m^2
1 km^2 (square kilometer) = 1000 m × 1000 m = 1,000,000 m^2= 100 ha

Gross vs. net fluxes

Gross fluxes are the total fluxes from, for example, deforestation or photosynthesis, whereas *net* fluxes account for the opposing flux as well. For example, net land use change fluxes account for both emissions from deforestation and degradation and sequestration from regrowth. Likewise, net productivity accounts for photosynthesis and respiration.

Biomass, carbon, and biomass or carbon density

The carbon content in biomass can be estimated from biomass using mean conversion values. The IPCC's Good Practice Guidance for Land Use, Land-Use Change, and Forestry reports a conversion factor of half or just less than half in their 2003 and 2006 reports, respectively. Thus, the amount of carbon in living vegetation can be determined as follows:

tons biomass (dry mass) $\times$ 0.5 = tons carbon (IPCC 2003) or tons biomass (dry mass) $\times$ 0.47 = tons carbon (IPCC 2006)

Carbon or biomass *density* refers to stocks per unit area (usually hectares; ha). Most ground-based research measures carbon in a certain area, such as 1-ha plots. Thus, total stocks can be determined by multiplying the average density by total area.

Agriculture, forestry, [other] land use, and land use change

Land fluxes are determined by the combination of fluxes from agriculture, forestry, other land use, and land use change. Agriculture is often considered separately and some terms, and combinations of terms are often used interchangeably. Thus, FOLU (Forestry and Other Land Use) is a subset of AFOLU (Agriculture, Forestry, and Other Land Use). LULUCF (Land Use, Land Use Change, and Forestry) and FOLU are often used interchangeably, though this can create some confusion as to whether agricultural emissions are included or not. For the sake of clarity, we will use the term FOLU, which includes conversion of land to agriculture but not subsequent emissions from agricultural practices. Deforestation dominates the FOLU flux, but it also includes new forest growth (e.g. afforestation or reforestation), urban expansion, etc. Scientific literature also uses LULUC or LULCC (Land Use and Land Use Change or Land Use and Land Cover Change), where forestry is implied within these classifications.

2. What is the role of forests in the global carbon cycle?

2.1 The basics: photosynthesis and respiration

In basic terms, forests are made up of trees and other woody and herbaceous vegetation, and their tissues (biomass) are made of nearly half carbon when water is discounted. Thus, forests hold carbon 'stocks' in living and dead biomass. 'Fluxes' refer to changes over time —living trees capture and release carbon via photosynthesis and respiration; dead tissues decay and release carbon; and a fraction of this carbon eventually ends up in the soils (Figure 2).

Trees and other plants continuously cycle carbon via photosynthesis, growth, respiration, death, and decay. They use energy from the sun and water from the soil to convert CO_2 from the atmosphere into photosynthates (sugars), water, and oxygen (O_2) via the process of photosynthesis. These photosynthates are used directly for cellular respiration and root exudation or they are stored as more complex molecules as an energy store or for growth of the leaves, stem, or roots. The mass of trees is often referred to as 'biomass', meaning 'living mass', and is composed of just less than half carbon by dry mass. When this growth is directed towards woody tissues (i.e., stem, branches, and large roots), it is called biomass accumulation. As with all living creatures, trees and other plants also use energy for maintenance and thus release CO_2 via respiration. The process of respiration is the reverse of photosynthesis: water and oxygen are used to break down organic compounds into energy, water, and CO_2. Plants photosynthesize when the conditions are right (i.e., when there is ample sunlight and moisture during the growing season), but they respire continually. Overall, photosynthesis generally exceeds respiration, making most terrestrial ecosystems net carbon sinks in a natural state.

Trees grow, but they also lose leaves and branches and eventually die. The leaves and small branches form the 'leaf litter' layer just above the soil surface, and larger branches and dead trees are called coarse woody debris (Figure 2). The dead plant material is decomposed by bacteria and fungi that consume much of the energy stored in the plant matter and therefore release CO_2 via respiration. Plant roots also die and decompose by the same process. Like every flow through the trophic levels, decomposition is an active process which releases most of the carbon stored in biomass, but some is retained. Ultimately, a small fraction of the carbon becomes soil organic matter, which is vastly important to support productive ecosystems – providing nutrients, water holding capacity, soil structure, and more. Peat is a special case of soil, consisting primarily of partially decomposed plant material that can build up to many meters in depth (Page, Rieley, and Banks 2011). Fire releases the carbon stored in biomass very quickly, though a small fraction of carbon remains in the ecosystem as incompletely burned ash and charcoal. Severe fires can even burn soil organic matter, releasing yet more carbon (Certini 2005), which is a particular problem in peatlands.

2.2 Global significance of forests in the global carbon cycle

Forests cover approximately 38.5 million km^2 (Pan et al. 2011) or 28 % of land surface (Hooke, Martín-Duque, and Pedraza 2012) and contain 77 % of all terrestrial above ground carbon (Houghton 2007). Total forest carbon stocks are estimated at 861 Gt C, which is 1.5 times more than all anthropogenic carbon emissions since the industrial revolution (555 Gt C) and over 3.5 times more than has accumulated in the atmosphere thus far (240 Gt; Ciais et al. 2013). Of the total forest carbon stocks, 363 Gt C are held in living biomass, 116 Gt C are in litter and dead wood, and 383 Gt C are stored in the soil (Pan et al. 2011).

Natural systems dominate the global carbon cycle. Terrestrial vegetation alone cycles over 120 Gt of carbon each year, taking up approximately 123 Gt C and respiring 119 Gt C (Ciais et al. 2013; Figure 2). This is about 15 times more than anthropogenic emissions from burning fossil fuels and producing cement each year (~8 Gt C). On land, these fluxes are dominated by forests, and the significance of forests in the global carbon cycle is demonstrated by intra-annual variation (variation within a year). The visible the sawtooth effect in figures showing atmospheric carbon concentrations corresponds to the growing season in the northern hemisphere, where the most land and forests exist (Keeling 1960). During the northern hemisphere summer, photosynthesis exceeds respiration globally and atmospheric CO_2 declines, whereas during the northern hemisphere winter, respiration exceeds photosynthesis and atmospheric CO_2 increases.

Forests have also played, and continue to play, a huge role in slowing the rate of climate change thus far. Mature and regrowing forests have been sequestering over 4 Gt of carbon each year since the 1990s (Pan et al. 2011; Figure 2). Thus, because of forests, atmospheric concentrations of CO_2 are not rising as rapidly as would be predicted by simply adding anthropogenic emissions to current levels in the atmosphere. Oceans are also absorbing an additional 2.3 Gt of carbon each year (Ciais et al. 2013). This phenomenon has been called a 'loan from nature' and a 'buffer to climate change' (Phillips and Lewis 2014). Though forests emit and capture more carbon every year than human activities, the problem is that human emissions are one-directional —emitting carbon with no subsequent sequestration on a large scale. Forests don't just capture and cycle carbon: they have other vital interactions with the atmosphere, climate, hydrological cycle, and nutrient cycle, which is discussed in further detail in Brandon (2014).

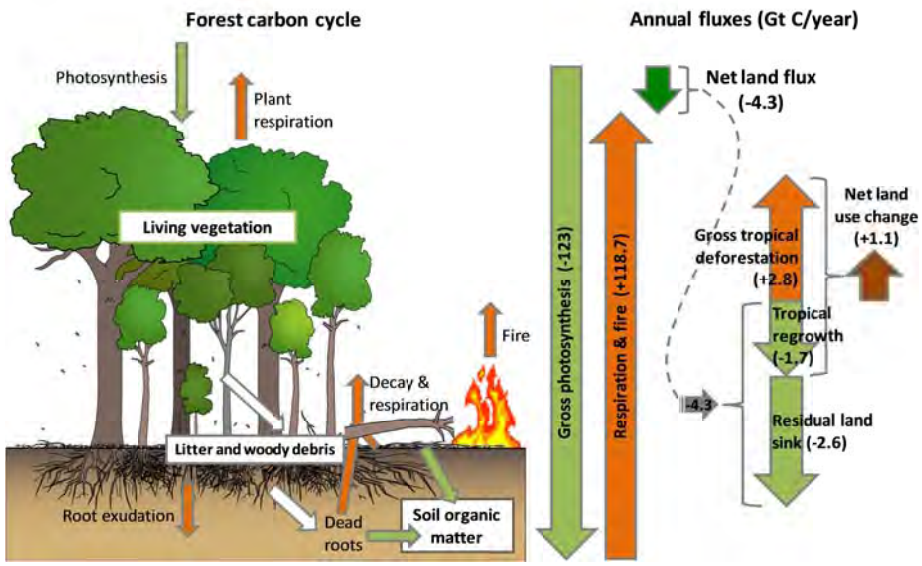

Figure 2. Schematic diagram of the forest carbon cycle. Green arrows represent sequestration of carbon from the atmosphere to plants or from plant material to soil organic matter. Orange arrows represent the release of carbon via respiration or combustion (fire). Annual fluxes are average gross terrestrial fluxes (2000–2009), which are dominated by forests, as reported in Figure 6.1 of the IPCC AR5 Working Group 1 (Ciais et al. 2013). The subset of land use fluxes (far right) are values reported in Pan et al. (2011) from 2000 to 2007.

3. Why do we focus on tropical forests?

3.1 Significance of humid tropical forests

Tropical forests are the largest, most carbon dense, and most diverse forests on Earth. Unfortunately, the high levels of deforestation within the tropics account for nearly all net forest loss and GHG emissions from FOLU across the planet.

Just over half of the world's remaining forests are found in the tropics (Pan et al. 2011). Tropical forests span 19.5 million km^2, 70 % of which (13.9 million km^2) are considered to be 'intact' (Pan et al. 2011). In total, tropical forests store approximately 471 ± 93 Gt C in live plants, soil, and necromass (dead plant material) (Pan et al. 2011). This number represents 55% of the global forest carbon stocks and is only 84 Gt C less than all anthropogenic emissions since the industrial revolution (555 Gt C) and nearly double what has accumulated in the atmosphere to date (240 Gt C; Ciais et al. 2013). Including regrowing forests, 72 % of all living forest biomass is found in the tropics. Every year, 72 Gt of carbon cycle through tropical forests and savannahs, representing 59 % of terrestrial gross primary productivity (the total influx of C from the atmosphere to plants per unit time) (Beer et al. 2010).

Per unit area, intact tropical forests hold more carbon than forests in temperate or boreal zones, 282 t C/ha on average (Pan et al. 2011). Considering the carbon in only living biomass, these forests store 2.7–3.5 times more carbon per hectare than temperate and boreal forests: 164 t C/ha in tropical forests vs. 61 t C/ha and 47 t C/ha in temperate and boreal forests, respectively (Pan et al. 2011) (Figure 3). Within, the tropics, forest biomass density is generally greatest in Southeast Asia, followed by Latin America, and Africa (Baccini et al. 2012, Saatchi et al. 2011). Tropical wetlands have even higher carbon densities: on average mangroves and peatlands store over 1,000 (Donato et al. 2011) and 2,000 t C / ha , respectively (Page, Rieley, and Banks 2011).

Since the 1990s, most deforestation and nearly all *net* forest loss occurs within the tropics (Hansen et al. 2013). Tropical forests also have the lowest proportion of cleared forests that are regrowing (Hansen et al. 2013). Thus, nearly all net emissions from land use change are from tropical regions (Pan et al. 2011). From 2000 to 2012, over 1.1 million km^2 of tropical forests were lost (Hansen et al. 2013). Annual net emissions from tropical deforestation over a similar time period (1999–2007) were 2.9 Gt C/year (Pan et al. 2011). Net emissions from FOLU in the tropics dominate global FOLU emissions because forests regrowth mostly compensates for emissions outside of the tropics, whereas deforestation greatly outpaces regrowth within the tropics (Houghton et al. 2012, Hansen et al. 2013). These dynamics are shaped by the different drivers of deforestation: most deforestation in the tropics is driven by land use change (i.e., conversion to agriculture; Hosonuma et al. 2012), where forests are more permanently lost. Conversely, forest loss outside the tropics is dominated by timber harvest and wildfires, after which forests regenerate (Hansen et al. 2013).

Beyond carbon, tropical forests are also home to over half of the world's known species (Terborgh 1992), and provide other locally and globally significant ecosystem services. Combined with their large role in the carbon cycle, these factors make tropical forest conservation a particularly attractive possibility for reducing carbon dioxide emissions and slowing global climate change, while potentially providing biological, environmental, and even social benefits (Phelps, Friess, and Webb 2012).

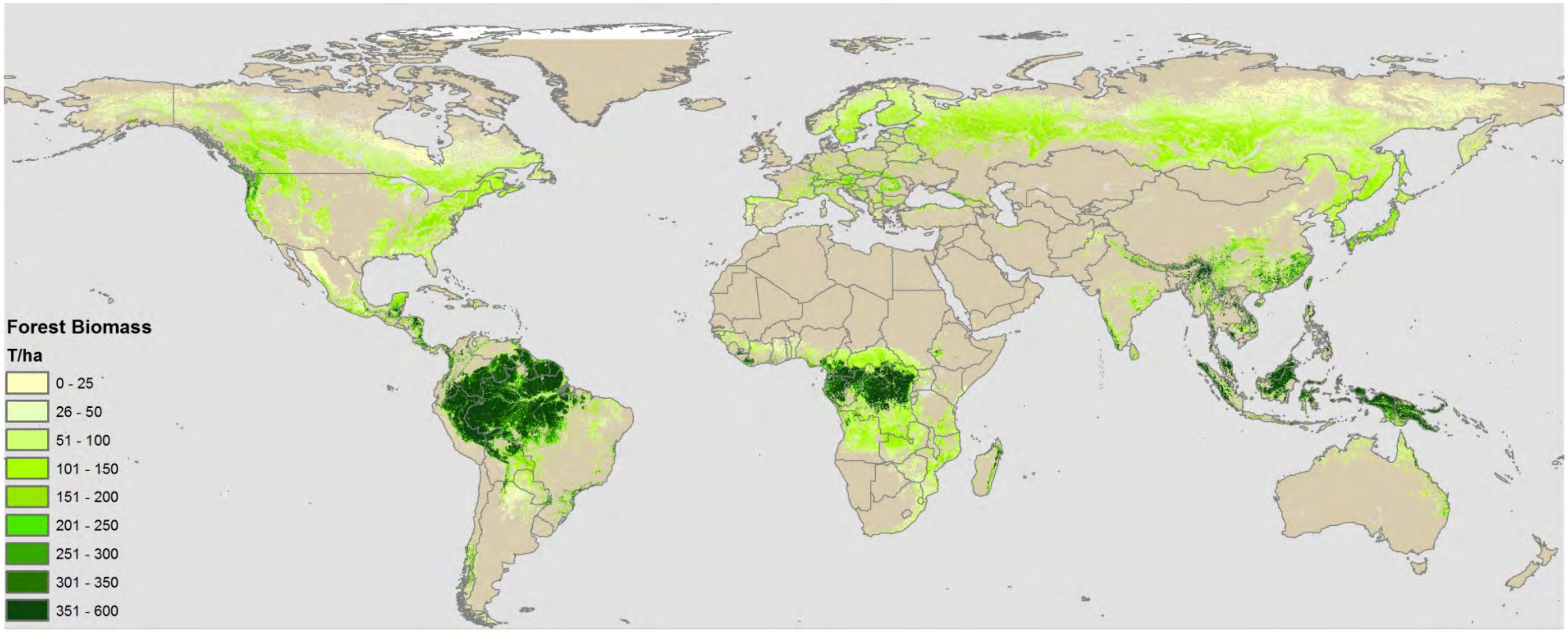

Figure 3. Map of biomass density (above- and belowground) in living vegetation across the globe. Tropical forests have the highest carbon density. Credit: Valerio Avitabile (Wageningen University).

3.2 Mature forests continue to sequester carbon

Multiple studies of the global carbon cycle conclude that terrestrial ecosystems serve as a net carbon sink (Le Quere et al. 2009, Pan et al. 2011), and a large part of this is owed to sequestration in mature tropical forests (Lewis, Lopez-Gonzalez, et al. 2009, Pan et al. 2011). As a silver lining to anthropogenic carbon emissions, the high concentrations of CO_2 in the atmosphere are thought to be increasing tree growth rates and biomass in some forests, which is referred to as 'CO_2 fertilization' (Lewis, Lloyd, et al. 2009, Norby and Zak 2011). Possibly as a result of this fertilization and other causes, mature tropical forests appear to be capturing over 1 Gt C each year, accounting for nearly half of the 2.3 Gt/year net terrestrial carbon sink in intact forests from 2000–2007 (Pan et al. 2011). Biomass and carbon stocks in mature, intact forests surveyed in Amazonia and Africa increased by 0.3 % per ha per year from 1987–1996 (Lewis, Lopez-Gonzalez, et al. 2009), though extrapolating these results to the continental scale remains somewhat controversial. Including tropical Asian forests, the tropical forest carbon sink has been estimated to total 1.2–1.3 Gt C each year (Lewis et al. 2009, Pan et al. 2011). To put this in perspective, a 0.3% increase in the biomass of mature forests in the Amazon alone absorbs about as much as all the entire fossil-fuel emissions in Western Europe each year (Phillips and Lewis 2014). On a global scale, mature tropical forests are believed to have been sequestering 14–17 % of all fossil fuel emissions from 2000–2011.

3.3 Significance of wetland forests

Wetlands —including peatlands, mangroves, swamps, and bogs— cover a relatively small area but store extremely high amounts of carbon per unit area. In contrast to upland tropical forests that hold most of their carbon stored in living biomass, wetlands store huge amounts of carbon in dead plant materials belowground (Figure 4). Globally, peatlands cover only 3 % of the land area but store roughly 350–550 Gt of carbon, approximately 20–25 % of all carbon stocks in soil organic matter (summarized in Smith et al. 2014). In the tropics, peatlands store 82–92 Gt C in just 441 thousand km^2 (Page, Rieley, and Banks 2011). This equates to over 2,000 t of carbon per hectare, an order of magnitude higher than carbon densities in upland, *terra firme* forests. Likewise, tropical mangroves cover approximately 138 thousand km^2 (Giri et al. 2011) along coastlines and are estimated to store an average of 1,023 t C/ha (Donato et al. 2011). These wetland forests are also small carbon sinks and provide a number of important ecosystem services (Smith et al. 2014), which are summarized in Brandon (2014).

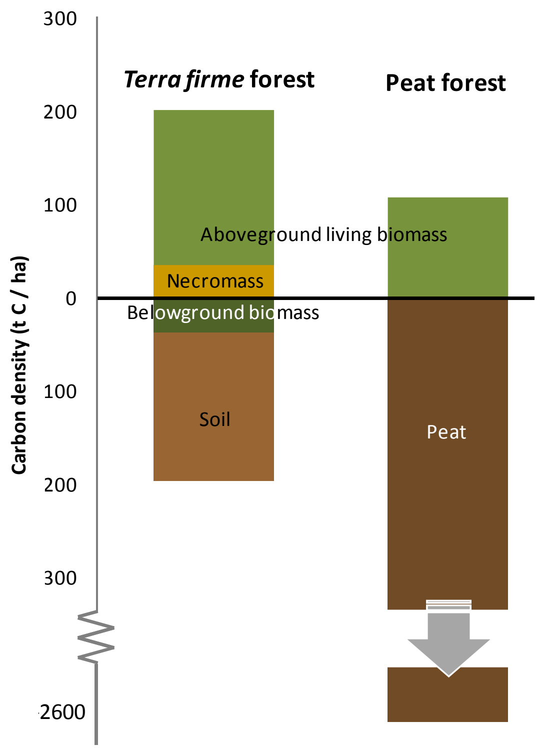

Figure 4. The contribution of different carbon pools in two forest ecosystems: mean carbon densities in Amazonian *terra firme* forests (data from Malhi et al. 2009) and Indonesian peat forests —aboveground data from Kronseder et al. (2012) and peat data from Jaenicke et al. (2008).

4. How do land use and land use changes affect carbon and other greenhouse gas emissions?

4.1 Deforestation and land use change

Deforestation occurs when a forest is completely cleared of trees and converted to another land use and the forest is not expected to regrow naturally and the emissions are owed to 'land use change'. Forests are cleared for commercial agriculture, subsistence farming, mining, infrastructure building, and urban development. Emissions from deforestation are determined by the product of the area cleared and average carbon density (i.e., t C/ ha) within that area, usually assuming that all carbon in biomass is lost during deforestation. All the carbon in biomass is 'committed' to being released, though it may take place slowly if the vegetation is left to decay or rapidly if burnt, as is the case for most land use conversion in the tropics. The decomposition and combustion of dead plant materials and soil organic matter also release other greenhouse gases, especially nitrous oxide and methane (Smith et al. 2014).

Due to the high carbon densities in wetlands, deforestation of these lands is particularly destructive. Draining peatlands increases aeration and therefore decomposition rates in these soils, leading to high CO_2, emissions over time. It also leaves them more vulnerable to fire, which releases yet more greenhouse gasses (Smith et al. 2014). Emission from draining and burning tropical peatlands is estimated around 0.3 Gt C per year (summarized by van der Werf et al. 2009, Houghton 2013). Despite covering a relatively small area, deforestation rates in mangroves are extremely high, resulting in emissions up to 0.12 Gt C each year (Donato et al 2011).

4.2 What land uses are replacing forests, and what are the implications for emissions?

Carbon is not only emitted when forests are cut and burned or left to decay, but subsequent land uses often result in further greenhouse gas emissions. Once forest is cleared (land use change), land management activities (land use and agriculture) cause GHG emissions, such as tilling soil, applying fertilizers, draining peatland, and using fire to clear vegetation.

Since the majority of deforestation is driven by agriculture — primarily industrial cattle ranching, soybean farming, and palm oil plantations for international markets in South America and Southeast Asia (Figure 7)— (Hosonuma et al. 2012), the land is subject to tillage and fertilizer applications. As is the case for draining peatlands, tilling increases aeration of mineral soil, thereby accelerating decomposition of soil organic matter and increasing the likelihood of erosion. The nitrogen fertilizer applied to crops can undergo chemical transformations in the soil and be lost to the atmosphere as nitrous oxide (N_2O). In this way, food production may be responsible for 80 % of the rise of nitrous oxide in the atmosphere (Ciais et al. 2013). Methane is second largest GHG in CO_2eq, and unlike the carbon cycle, the global methane cycle is dominated by humans (~50 %) (Ciais et al. 2013). Ruminant livestock, such as cattle, and rice paddies are responsible for vast quantities of methane emissions.

Biofuel crops can in theory save GHG emissions if they are used to replace fossil fuels and the average carbon stock of the biofuel crop is higher than the carbon stock of the land use system they are replacing. However, the production of biofuel crops also emits GHGs from nitrogen fertilizers, diesel fuel, and – most importantly– direct land use change. The direct conversion of native forests, woodlands, wetlands, or grasslands to biomass cropping systems usually results in net GHG emissions, rather than savings, because the native ecosystems they replace are very carbon-rich (summarized in Smith et al. 2014). Oil palm plantations to produce palm oil-based biodiesel, for example, can take 170–300 years to become carbon-neutral if the plantations replace peatlands (Wicke et al. 2008). On the other hand, palm oil plantations can become carbon neutral within 8–16 years when planted on previously-cleared mineral soils (Wicke et al. 2008). Plantation forestry is emerging as a driver of intact forest losses (Hansen et al. 2013): over half (54 %) of forest plantations are found in Asia and the Pacific, but they have also risen in Latin America and Africa (Blaser et al. 2011).

Subsistence agriculture is responsible for 27–40 % of deforestation in the tropics and is second only to industrial agriculture with respect to area of deforestation (Hosonuma et al. 2012). Farmers in these systems are less likely to apply fertilizers and more likely to fallow land as part of a shifting cultivation cycle. Thus, carbon stocks can temporarily increase as forests regenerate in abandoned agricultural lands, but croplands and pastures themselves have very little biomass (Figure 5).

Mining and urban expansion account for small proportions of total deforestation, but can be particularly devastating. Forests will never grow back after urbanization and may be nearly as impeded after mining. Gold mining, for example, is increasing in the western Amazon, causing deforestation, severe soil disturbance and degradation, and mercury contamination (Asner et al. 2013). Surface mining removes all vegetation and topsoil, leaving the remaining soil severely degraded —compacted; devoid of nutrients, organic matter, and microbes; and often acidic with high levels of toxins (Sheoran, Sheoran, and Poonia 2010). Thus, huge quantities of carbon and other greenhouse gases are released (Jaramillo et al. 2007) and forest regrowth is severely impeded, even with serious afforestation or reclamation efforts (Huttl and Weber 2001, Sheoran et al. 2010).

Box 2, *FAQ 1. Why can't we just cut down mature forests and plant fast-growing tree species, so that they can more actively sequester carbon?*

When mature forests are cut, a lot of carbon is released quickly, or even immediately when burnt. In contrast, tree plantations accumulate carbon in biomass over time (Box 4, Figure 5) and may never reach the carbon stocks of mature forests if they are cut on short rotations. Because plantation forests are destined to be harvested, the carbon accumulated in these trees is far less permanent than in primary forests under conservation and only a small share of carbon ends up in long-lived wood products (see Box 3, FAQ 5).

Approximately 7% of all tropical forests are planted, most of which are intensive fast-rotation plantation systems (FAO 2010), and plantation forestry is a leading driver of intact forest loss (Hansen et al. 2013). Numerous studies demonstrate why converting natural forests to plantations is not a good idea for the climate. For example, converting natural forests to plantations has resulted in net carbon losses (Yang et al. 2007) and reduces soil carbon (Guo and Gifford 2002). In Indonesia, experts give strong warnings against focusing on expanding plantations rather than reducing deforestation and peatland degradation: meeting emissions targets would require a land area double the size of the entire country (Verchot et al. 2010). Of course, the carbon balance of converting native forests to plantations depends on the forests being replaced, but the carbon benefits also rely on the survival and growth of the planted trees, which may be very low (Cao et al. 2011). Fertilizers may also be applied to achieve fast growth rates, which can result in more powerful GHG (N_2O) emissions.

Though growth in forest plantation rates are generally fast during the first few decades of stand development (Ryan, Binkley, and Fownes 1997), new research is showing that large trees in mature forests continue to sequester substantial amounts of carbon (Stephenson et al. 2014). Individually, large trees grow faster than small trees: in a meta-analysis, trees with 100 cm diameters accumulated 103 kg biomass/year on average (3 times higher than the average growth rate of trees with half their diameter and the equivalent of adding a new tree each year), and the largest trees can accumulate over 600 kg biomass each year (Stephenson et al. 2014).

Biodiversity and ecosystem services are also compromised by converting native forests to plantations, which may have implications for carbon fluxes and climate change. Furthermore, plantations, which have very low biodiversity compared to native forests, may be less resilient to climate change than primary forests (Thompson et al. 2009). In terms of biodiversity, forest structure, and conservation value, primary forests are simply irreplaceable (Barlow et al. 2007, Gibson et al. 2011, Chazdon 2008).

4.3 Degradation

Forest degradation, in carbon terms, refers to the removal of carbon in forests remaining as forests, which are expected to regrow naturally. Thus, the carbon emissions come from 'land use and forestry', but there is no land use *change*. Examples include selective logging, fuelwood collection, charcoal production, fires, repeated fire escaping from nearby cleared land, and livestock grazing under trees (Figure 5). As is the case with deforestation, all the carbon in dead biomass is 'committed' to being released, though this generally decays slowly over time unless fire burns the dead materials. In the Amazon, emissions from selective logging can continue for decades after a timber harvest (Huang and Asner 2010). Only a small fraction of the carbon extracted during timber harvests ends up in long-lived wood products (see Box 3, FAQ 5).

In the tropics, timber extraction and logging is the responsible for just over half of forest degradation (52 %), followed by fuelwood collection and charcoal production (31%), uncontrolled fire (9 %), and livestock grazing (7 %) (Hosonuma et al. 2012). Like the drivers of deforestation, drivers of degradation vary by continent: Selective logging is the main driver of degradation in South America and Asia (> 70 %), but fuelwood collection is the most important driver in Africa (Hosonuma et al. 2012; Figure 7). Though total forest cover has declined in the tropics, forest area designated for production has increased from 2005 to 2010 —at the expense of protected natural forests— in Latin America and Asia (Blaser et al. 2011). Uncontrolled fires can also be important and are most common in Latin America (16 %) (Hosonuma et al. 2012). On average, livestock grazing contributes less than other sources of degradation, but accounts for 9 % in Africa (Figure 7).

Forest degradation is much more difficult to detect remotely and to quantify than deforestation. Forests remain forests, but their carbon stocks (Bunker et al. 2005) and ecosystem services (Foley et al. 2007) are reduced. The extent to which they are reduced varies greatly. Degradation is responsible for approximately 12–16 % of carbon emissions from tropical forests (Huang and Asner 2010, Houghton 2013, Pearson et al. 2014), but a majority of these emissions may be 'offset' by forest regrowth (Figure 11.8; Smith et al. 2014).

An alternative perspective is that managing forests for both timber and non-timber forest products offers an economic alternative to clearing the land entirely and is one of the most successful tools for resisting deforestation (Griscom and Cortez 2013). Despite the reductions in carbon, biodiversity, and ecosystem services (compared to primary forests), degraded forests still provide many benefits of forests. Compared to other disturbances, selective logging had the lowest detrimental effects on biodiversity (Gibson et al. 2011). In theory, forests can be managed sustainably, by reducing forest degradation and even enhancing forest stocks, though the practicalities of this are still lacking in the tropics. In the meantime, practicing reduced impact logging techniques is a step in the right direction – reducing many of the negative environmental impacts and carbon emissions while maintaining timber supply (Putz et al. 2008, Putz et al. 2012).

4.4 Why is fire significant?

In tropical rainforests, fires are almost always started by humans, by both disturbances and ignition (Bush et al. 2008). Opening or removing the canopy allows light to penetrate and dry vegetation past a point of flammability, whether that is intentional or not. Fire is used as a tool to clear forests initially and to maintain pastures from woody encroachment. Unfortunately, fires often escape from their intended area and burn out of control in natural forests. They are a serious and imminent threat to tropical forests, are more frequent during droughts associated with El Niño events, and thus may increase with climate change (Bush et al. 2008). Fires degrade the forests and reduce carbon stocks in aboveground vegetation. Intense fires can even burn the soil, which both releases carbon and can sterilize the top layer (i.e., kill all microbes), thus altering carbon and nutrient cycling (Certini 2005).

Burning trees and other plants not only releases CO_2 into the atmosphere, but also more potent greenhouse gases, such as CH_4, N_2O, ozone-precursors, and aerosols such as black carbon (Ciais et al. 2013). When biomass is burned, but the combustion is not complete, fine particles of black carbon (soot) are released into the atmosphere. Though it is not a gas, its ability to warm the atmosphere is enormous: by weight, these particles can absorb a million times more energy than CO_2 (US EPA 2012). Globally, open biomass burning, including wildfires, is the largest single source of black carbon emissions, 35.5 % (Lamarque et al. 2010, US EPA 2012). Fortunately, black carbon is short-lived in the atmosphere, which also means that reductions in black carbon emissions will give more immediate climate benefits (Carmichael et al. 2013).

In total, fire emissions from deforestation and degradation in the tropics are estimated at 1.4 Gt CO_2eq per year, though the carbon emitted from fire is already included in deforestation and degradation accounting (Smith et al. 2014). Non-CO_2 emissions from deforestation, forest management and degradation, and peatland fires totaled roughly 0.3 Gt CO_2eq in 2010 (FAOSTAT 2013, Smith et al. 2014).

4.5 Forest regrowth

Forest regrowth is a general term for the growth of both pre-existing forests and new forests. New forests in previously cleared lands can begin via natural regeneration (from a residual seed bank and new seeds dispersed by the wind, water, and animals) or be actively planted by humans. Reforestation refers to planting trees in an area that was once forest, afforestation refers to planting trees in areas that were not previously forested, and their carbon fluxes are included in the 'land use change' category. Existing forests are always growing and recovering from disturbances. This is usually a natural process, but regrowth and forest dynamics can be altered by management activities, such as enrichment planting of desired species and removing vines from future crop trees.

Forest regrowth 'offsets' much of the carbon emitted by land use and land use change because trees sequester carbon from the atmosphere as they regenerate after being cleared and regrow after less severe disturbances and degradation. Net emissions from FOLU in the forestry sector are therefore calculated as gross emissions from deforestation and degradation minus the carbon sequestered from forest regrowth. In the tropics, forest regrowth (forests regenerating after deforestation and recovering from selective logging) captured 1.2–1.7 Gt carbon of per year in the 1990s and 2000s (Houghton 2013, Pan et al. 2011). This reduces net emissions from land use change to around half of the gross emissions from deforestation. The implications of gross vs. net emissions are discussed further in section 6.2.

However, it should be noted that secondary forests and forests subjected to intensive or repeated selective logging are not the same as intact, primary forests (see Box 2 for more details). Secondary forests have much lower biomass than primary forests (Pan et al. 2011), and degraded forests may take over one (Huang and Asner 2010) or even two (Riswan, Kenworthy, and Kartawinata 1985) centuries to recover lost biomass. The ability of forests to regenerate and regrow, and the rates of this growth, are dependent on the type and severity of disturbance, ecosystem dynamics, climate, species, and human interventions (Box 4).

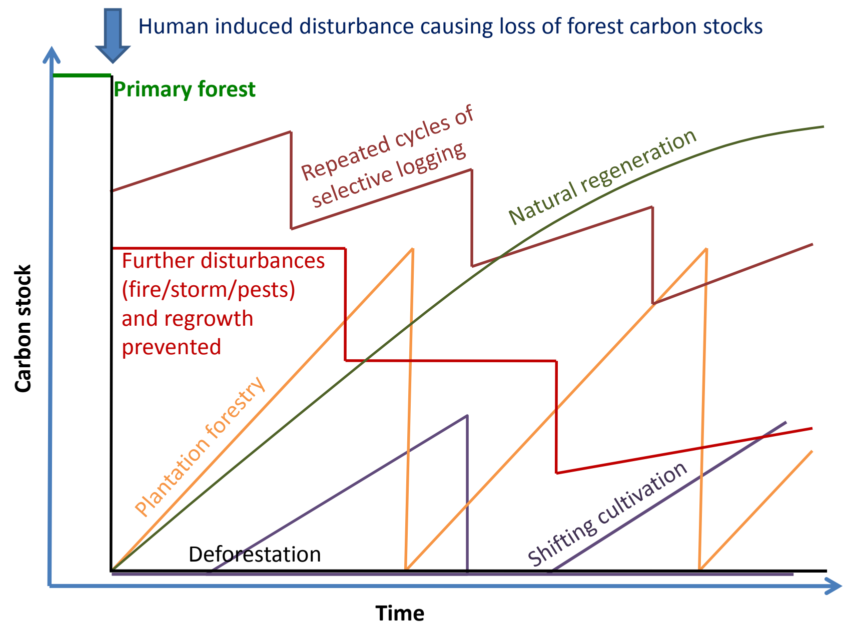

Figure 5. Conceptual diagram showing the effect of different human induced disturbances, land uses, and forest management on forest carbon stocks.

5. Relative significance of forest-based emissions in total emissions

5.1 How significant are emissions from tropical deforestation and degradation?

Net emissions from Forestry and Other Land Use (FOLU) in the tropics dominate the global FOLU emissions. Net emissions from FOLU made up 11 % of total GHG emissions (in CO_2 equivalents) in 2010, which is predominately from tropical deforestation and forest degradation and is slightly less than emissions from transportation (14 %) (Edenhofer et al. 2014). The vast majority of FOLU greenhouse gas fluxes are carbon itself —from deforestation, degradation, soil, regrowth, and afforestation— and FOLU carbon emissions account for approximately 11–15 % of all CO_2 emissions in 2010 and 12–16 % in the 2000s (Table 1) (Edenhofer et al. 2014, Pan et al. 2011, Houghton 2013). Non-CO_2 emissions are smaller and arise mostly from fires and peatland degradation (Ciais et al. 2013).

Net emissions from FOLU are proportionally lower in the most recent IPCC report than in past IPCC reports, reflecting both a slight decline in forest-based emissions over the past decade and, more significantly, a huge increase in fossil fuel and industrial emissions (Figure 6A). Circa 1970, over half of all cumulative CO_2 emissions to the atmosphere had come from FOLU, following the expansion of agriculture in the 19th and 20th

centuries. However, over the last 65 years, GHG emissions have soared from all sectors (especially energy supply, industry, and transport), while emissions from FOLU have remained fairly steady and perhaps even decreased very recently. Thus, circa 2010, cumulative emissions from fossil fuel, cement, and flaring have emitted nearly two times more CO_2 than forestry and other land use, and the relative contribution of FOLU to cumulative emissions has been reduced (Ciais et al. 2013) (Figure 1). Net emissions, however, may be misleading (see section 5.3 and Figure 6B).

Finally, records show that tropical forests can release globally significant quantities of carbon into the atmosphere. Year to year fluctuations and anomalies seen in the annual atmospheric CO_2 accumulation may be primarily driven by fluxes in tropical forests. Large spikes in atmospheric CO_2 concentrations correspond to El Niño events (Baker et al. 2006), demonstrating how tropical forests influence the global carbon cycle — drought reduces net CO_2 uptake in trees, mortality from severe drought releases carbon over time, and fire releases carbon immediately. Thus, the carbon sink is reduced and carbon sources increase.

5.2 How have the rates of tropical deforestation and forest degradation and associated emissions changed over the past 30 years?

Deforestation and forest degradation rates and trends have changed in the last several decades. Prior to the 1930s, emissions from FOLU were greater in the northern latitudes but have been dominated by deforestation in the tropics since 1960 (Houghton 2013). Since 1990, nearly all net FOLU emissions are from the tropics (Houghton 2013). Though deforestation and degradation still exist outside the tropics, forest regrowth nearly neutralizes net carbon emissions there (Houghton 2013). Gross tropical deforestation rates have been estimated at 8 million ha/year on average during the 1990s and 7.6 million ha/year from 2000–2010 (Achard et al. 2014) but rose steadily within this century (Hansen et al. 2013). Emissions from deforestation were greatest in the 1980s (rising from about 1 to over 1.6 Gt C /year), declined rapidly during the 1990s and early 2000s, and returned to just over 1 Gt C/year by 2010 (Houghton 2013). Net carbon emissions from net FOLU over the last three decades have been estimated at 1.4 Gt C/year in the 1980s, 1.5 Gt/year in the 1990s, and 1.1 Gt/year in the 2000s (Ciais et al. 2013), thus accounting for 19, 20, and 12 % of total anthropogenic carbon emissions in each of the three decades, respectively (Figure 6A). Over the same time periods, the residual land sink has removed 22, 32, and 29 % of total anthropogenic carbon emissions from the atmosphere.

5.3 Gross vs. net emissions and sinks

Net land use change emissions may be misleading, as it combine two separate and larger fluxes: gross emissions from deforestation and sequestration via forest regrowth. Gross emissions from tropical deforestation and degradation were estimated at an average of 2.6–2.8 Gt C/ year from 2000–2007 (Pan et al. 2011) or 1990–2010 (Houghton 2013), which would account for over a quarter of total anthropogenic carbon emissions from gross deforestation, fossil fuels, and cement in the 2000s (Figure 6B; Table 1). However, regrowing tropical forests captured 1.7 Pg C/ year (Pan et al. 2011), bringing the net LULUCF flux down to < 40 % of the gross LULUCF flux. If the two fluxes (sources and sinks) are separated, forest regrowth reduces net FOLU emissions by 46–61 % in the tropics. Sequestration in intact forests is not included in the FOLU flux, but when the sinks in regrowing and in intact forests are combined together and compared against gross emissions, tropical forests sequestered 30–35 % of total C emissions in the 2000s (Table 1), and the global land sink removed approximately 38 % of anthropogenic carbon emissions in the 2000s (Figure 6B). Finally, the difference between gross deforestation emissions (2.6–2.8 Gt C/ year) and the total land sink (-4 Gt C/ year) shows the enormous potential of the forestry sector to both reduce emissions and enhance sequestration worldwide (more than 6.5 Gt C/ year). This potential is estimated at 4.8–5.6 Gt C/year in tropical forests alone from 2000 to 2007. If deforestation had been halted and regrowth allowed to continue at its current rate, tropical forests would have removed 30–35 % of anthropogenic C emissions during the 1990s and 2000s and 25–30 % of emissions in 2010 (Table 1). The entire terrestrial sink would have removed over half of all carbon emissions in the 2000s (Figure 6B).

The Pan et al. (2011) flux estimates are consistent with those reported in the IPCC AR5 Working Group 1 chapter on the carbon cycle (see Figure 2). However, other pantropical analyses have determined similar net emissions from FOLU, but lower gross fluxes. Two independent studies using new applications of remote sensing techniques estimated that gross and net tropical deforestation emitted approximately 0.8 Gt C / year from 2000–2005 (Harris et al. 2012) and 2000–2010 (Baccini et al. 2012). Adding emissions from degradation, shifting cultivation, and soils brought net emissions to 1.0–1.1 Gt C/year from tropical FOLU (Baccini et al. 2012, Houghton 2013), and including draining and burning peatlands brings net emissions estimates to 1.4 Gt C/ year from 1990–2010 (Houghton 2013). However, these studies show lower gross fluxes, especially sequestration in regrowing forests than Pan et al. (2011). Gross emissions were estimated at 2.3 Gt C/ year (Baccini et al. 2012) or 2.6 Gt C/ year including draining and burning peatlands (Houghton 2013). Both studies estimated that regrowth removed only 1.2 Gt C / year in tropical forests (Baccini et al. 2012, Houghton 2013). Using these figures, the potential for total potential for tropical forests to mitigate climate change is lower but still very large, more than 4.5 Gt C/ year (including carbon absorbed in intact forests). Though there is still uncertainty in global estimates, many independent studies show that tropical forests play a large and important role in the global carbon cycle.

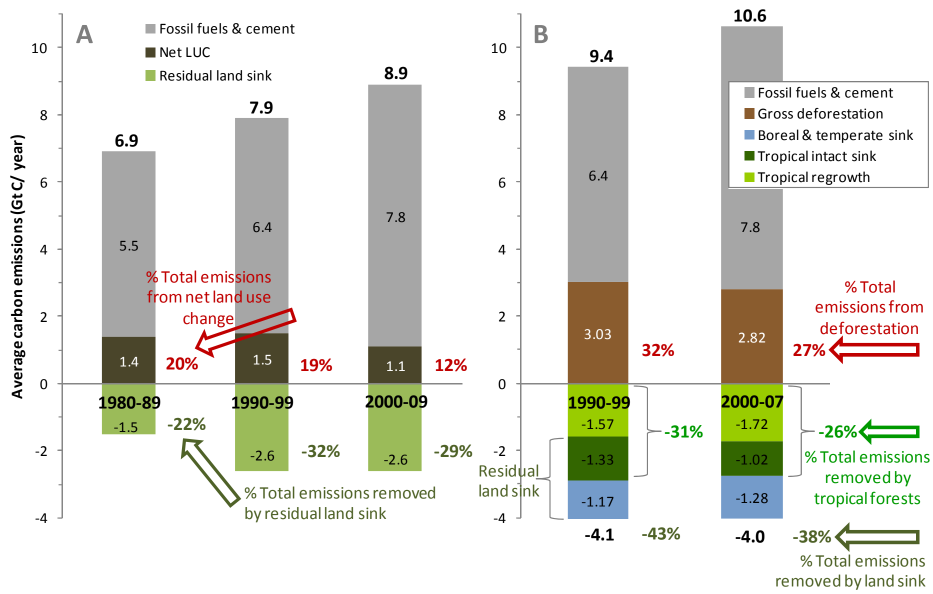

Figure 6. (A) Average annual anthropogenic carbon emissions from fossil fuels and cement and net land use change (deforestation – tropical regrowth) and residual land sink over each of the last three decades as reported in Table 6.1 in the IPCC AR5 WG1 (Ciais et al. 2013). (B) Annual emissions where tropical deforestation and regrowth are separated, as is the residual land sink, over a similar period (1990–2007) (data from Pan et al. 2011). The time periods studied and numbers do not align exactly between the two sources for the residual land sink (A) and its component parts (B), as these are the most uncertain of all carbon fluxes.

Table 1. Summary of emissions and sequestration in tropical forests estimated by three different studies, three global carbon emissions scenarios —as reported in the IPCC AR5, an alternative way of calculating global emissions (using gross tropical FOLU emissions or excluding sequestration from regrowth and two theoretical scenarios), and one hypothetical scenario of no tropical FOLU emissions—, and four estimates of the role of tropical forest emissions and sequestration in the global carbon cycle.

		Sequestration in tropical forests			Emissions from FOLU		Global carbon emissions scenarios					
							Reported in IPCC AR5		Including gross FOLU emissions		If no FOLU emissions	
Source	Time period	Regrowth	Mature forests	Total sink	Gross	Net	2010*	2000s	2010	2000s	2010	2000s
Pan et al. (2011)	1990-2007	1.6	1.2	2.8	2.9	1.3	10.2	9.9	11.8	11.5	8.9	8.6
Pan et al. (2011)	2000-2007	1.7	1.0	2.7	2.8	1.1	10.2	8.9	11.9	10.6	9.1	7.8
Houghton (2013)	1990-2010	1.2	1.0**	2.2	2.6	1.4	10.2	8.9	11.4	10.1	8.8	7.5
Baccini et al. (2012)	2000-2010	1.2	1.0**	2.2	2.3	1.0***	10.2	9.9	11.4	11.1	9.2	8.9

		Role or potential role of tropical forests in global carbon cycle						
Source	Time period	Removed by tropical forest sink (2000s)	Emissions from net FOLU		Emissions from gross FOLU		Sequestered if no FOLU emissions	
Pan et al. (2011)	1990-2007	25%	13%	13%	25%	25%	32%	33%
Pan et al. (2011)	2000-2007	26%	11%	12%	24%	27%	30%	35%
Houghton (2013)	1990-2010	22%	14%	16%	23%	26%	25%	30%
Baccini et al. (2012)	2000-2010	20%	10%	10%	20%	21%	24%	25%

*Carbon estimated as (11% + 65%) × (49 Gt CO_2-eq emissions in 2010) × (1 t C / 3.66 t CO_2), where 11% and 65% are the CO_2 contributions of FOLU and Fossil fuel and industrial processes, respectively

**Using the Pan et al. (2011) estimate for the sink in intact tropical forests from 2000-2007 as a conservative estimate

***Reported as 1.0 in Baccini et al. (2012) but as 1.1 in Houghton (2013)

5.4 Changes between the 4th and 5th IPCC Assessment Reports and since

Since the IPCC's Fourth Assessment Report (AR4) (Denman et al. 2007), more data and better modeling have improved flux estimates from FOLU (Ciais et al. 2013). Namely, there have been updates to country statistics on land use changes (FAO 2010) and new forest inventory data to estimate biomass carbon gained in forest regrowth, though data remains limited in the tropics (Pan et al., 2011). Thus, land use change flux estimates are considered to be more robust (e.g., Houghton et al. 2012), and the uncertainty associated with these flux estimates has been reduced to roughly half that reported in the AR4 (Ciais et al. 2013). Since the Fifth Assessment Report (AR5), several remote sensing studies have independently evaluated forest biomass changes, which we have included in this paper.

Most studies agree that carbon emissions from FOLU (mostly deforestation) have been declining in the past decades. However, new analyses (published since data used in the AR5) suggest that tropical deforestation may be higher than previously estimated and increasing again (Hansen et al. 2013).

Box 3. Frequently asked questions

FAQ 2. If the most recent IPCC report (AR5) says that the percentage of total emissions from forests has gone down since the last assessment report, doesn't that mean that we're solving the problem?

Unfortunately, we are far from solving the problem of climate change or deforestation. The proportion of emissions from FOLU has decreased since the last IPCC report primarily because emissions from all other sectors, especially energy, have skyrocketed. Nonetheless, the IPCC found a decline in deforestation rates and increase in afforestation, thereby reducing FOLU emissions, and projected that this trend may continue (Edenhofer et al. 2014). However, even if rates of deforestation were declining in the 2000s relative to previous decades, huge amounts of irreplaceable primary tropical forests have been lost (deforestation) and marginalized (degradation) each year. It is also important to note that when we remove forests, it not only releases carbon but also removes their ability to safely sequester carbon from the atmosphere, which is a necessary component in achieving long-term climate goals. Indeed, vegetation is one of, if not the only, safe place for carbon sequestration. CO_2 absorbed by the oceans causes dangerous acidification and carbon capture and storage technologies are thus far still experimental. Furthermore, an update since the Fifth Assessment Report suggests that rates deforestation may be rising again (Hansen et al. 2013).

FAQ 3. Aren't forest-based emissions different and less problematic than emissions from fossil fuels because forests grow back, while oil wells don't?

Isn't the regrowth of forests in places like China cancelling out deforestation elsewhere?

Though, these two questions are different, they will be answered in tandem. First, it is important to note that any carbon dioxide in the atmosphere is the same molecule and has the same greenhouse effect as every other CO_2 molecule in the atmosphere, whether it came burning fossil fuels or forests. Thus, no CO_2 emissions are any less problematic than any other. Forests do have the potential to regrow after disturbances, but they will be different from primary forests and may never recover their original structure or diversity of life. In terms of carbon, there are different ways to look at this problem. One perspective is to deduct the carbon captured during forest regrowth from the emissions from deforestation each year to estimate net emissions from land use change. This method may reflect cycles of shifting agriculture, for example, where there land is cleared of forest, cultivated for a period, and then left fallow (Figure 5). However, the majority of deforestation is caused by large scale land conversion, such as ranching in the eastern and southern portions of the Brazilian Amazon Basin and palm oil plantations in Indonesia, and forest regrowth is usually not linked to this land clearing. Thus, large-scale reforestation efforts, as have been undertaken by China in the past decade, are not offsetting CO_2 from tropical deforestation *per se*. Rather, carbon sequestration in intact and regenerating forests are removing CO_2 from the atmosphere as a whole, which reduces the rate of CO_2 accumulation in the atmosphere in general as opposed to specifically 'offsetting' emissions from deforestation and land use change.

Two more important lessons can be learned from China's afforestation program. First, it demonstrates the global significance that policy-driven actions can make removing CO_2 from the atmosphere. From the 1990s to the 2000s, China's carbon sink in biomass was reported to almost double as a result of their national reforestation/afforestation program (Pan et al. 2011). Secondly, for afforestation to be an effective climate change mitigation strategy, the trees must survive and thrive. Unfortunately, recent research indicates that afforestation efforts in China may have had low survival rates because they were not adapted to local conditions (Cao et al. 2011).

FAQ 4. Isn't carbon stored in forests less "permanent" than carbon stored in other ways?

It is true that carbon stored in forests (vegetation and soils) is not permanently stored, but most emissions reductions are not. Not using fossil fuels, for example, only avoids emissions so long as they are not used. Few mitigation actives are considered permanent (that is, once the emissions are avoided, they cannot be re-emitted). From the forestry sector, substituting biofuels in place of fossil fuels and wood products in place of more energy-intensive materials are considered permanent or irreversible (Smith et al. 2014). Unlike fossil fuels, however, the carbon in trees and soil has the additional threat of being released via climate change itself and associated natural events (i.e., mortality or reduced growth from drought, pests, or fire). Fortunately, because forests have the ability to regrow, any loss of carbon stocks may also be only temporary. Despite this threat of 'non-permanence' or 'reversibility', it is important to reduce emissions immediately —from forestry, agriculture, energy production, and all other sectors.

FAQ 5. How significant is the carbon "locked up" in furniture, paper, and other forest products?

The role of carbon 'locked-up' in long-lived wood products (> 100 years), such as furniture and buildings, is small. From 1900 to 2008, only 0.035–0.091 Gt C has been stored in this way each year, totaling 6.9 Gt C in over a century (Lauk et al. 2012) – less than 4% of the total emissions from land use change since the industrial revolution. Though this is not a negligible amount in total, locking carbon in wood products has very limited potential in terms of climate change mitigation (Lauk et al. 2012). Conversely, the primary benefit in terms of reducing GHG emissions can be gained from using wood products instead of energy-intensive materials such as concrete, steel, and aluminum (Sathre and O'Connor 2010).

Unfortunately, harvesting wood is a fairly inefficient process, and wood harvested in tropical countries has the lowest proportion that ends up in long-lived wood products (Earles, Yeh, and Skog 2012). Carbon is lost from the forest during the timber harvest and extraction and when the wood is processed. First, when a tree is felled, it damages and kills surrounding trees as it falls ('collateral damage'). Second, large portions of the harvested tree are left in the forests: 'crop tree residuals' include the branches, stump, buttresses, and any unusable portions of the trunk, such as hollow or rotten sections. Third, skidding the commercial trunk to the road is often performed with large tractors that plow over small trees in its path and disturb the soil. Once the commercial roundwood is extracted from the forest, over half of the original roundwood is lost as it is sawn into lumber (Abebe and Holm 2003). Finally, 2–6 times more wood ends up in landfills each year than in long-lived wood products (Lauk et al. 2012, Pan et al. 2011). Thus, of the 3.4 billion cubic meters of wood removed in 2005 (FAO 2010), only about 0.064 Gt C would end up in long-lived forest products on average, but several orders of magnitude more carbon is emitted during the process. This represents only 2 % of the average annual carbon emissions from tropical deforestation (2.82 Gt C; Pan et al. 2011).

6. Current and projected rates of emissions from deforestation and degradation

6.1 Current rates and hot spots for deforestation and forest-based emissions

Deforestation in the tropics is the main source of global FOLU emissions. Though rates of tropical deforestation are lower than past decades, they are still high and global forest cover is still decreasing. From 2000 to 2012, 1.1 million km² of tropical forest was lost, compared to only 0.25 million km² of new forest regrowth (Hansen et al. 2013). On average, 92 thousand km² of tropical forests are lost each year with a net loss of 77 thousand km² lost each year. Global hotspots for deforestation remain in South America, especially in Brazil's 'arc of deforestation' along the southern border of the Amazon, and in Southeast Asia, especially Indonesia (Figure 7). Within the tropics, by far the highest levels of deforestation occur in Brazil and Indonesia, followed by China, Democratic Republic of the Congo, Malaysia, Argentina, Paraguay, and Bolivia (Hansen et al. 2013). Many other smaller and less forested countries, such as Benin, Cote d'Ivoire, Ghana, Uganda, Uruguay, Zimbabwe, and Zambia, show alarmingly high rates of forest lost relative to forests remaining (Hansen et al. 2013).

Many studies have documented a reduction in rates of deforestation over the past 10–15 years, but this trend may be reversing. Since the most recent IPCC reports (2013 and 2014), new research has found that rates of tropical deforestation are higher than previously estimated and actually increasing by 2101 km²/ year in the tropics (Hansen et al. 2013). From 2000 to 2012, the rates of deforestation in Brazil reduced by 1,318 km²/year on average (with a high of >40,000 km²/ year in 2004 to a low of < 20,000 km²/ year in 2011), while rates in other tropical regions increased by over twice this amount (Hansen et al. 2013). Within Brazil's Legal Amazon, deforestation is reported to have reduced to less than 5,000 km²/ year in 2012 (INPE-PROJETO PRODES 2014). Deforestation in other countries rose by 2,731 km²/ year, 64 % in Eurasian tropical forests, 20 % in African tropical moist forests, and 17 % South American dry forests. Deforestation rates in Indonesia climbed by 1021 km²/ year and reached a maximum during the last year of the study: over 20,000 km^2 of forest were cleared from 2011 to 2012. Deforestation rates also increased in Malaysia, Paraguay, Bolivia, Zambia, and Angola (Hansen et al. 2013). Over half of all peatlands drained were in Asia (Smith et al. 2014), and mangrove ecosystems have been reduced by 20 % since 1980 (FAO 2007).

Degradation is also a significant source of gross emissions and affects large land areas. In contrast to the clear deforestation hotspots, forest degradation both less easy to detect and perhaps more pervasive. Figure 7 shows that much of the central Amazon is nearly undisturbed, but low levels of emissions occur throughout African woodlands. These patterns are aligned with the drivers of degradation in these continents. Industrial logging, the primary driver in Latin America and Asia, will occur where access is better near forest frontiers, whereas fuelwood collection and livestock grazing in Africa can degrade forests at a much lower level over a larger scale. Many countries in the Congo Basin and elsewhere in Africa (e.g., Democratic Republic of Congo, Angola, Zambia, and Mozambique) have high forest cover and are relatively undeveloped (Hosonuma et al. 2012), but are threatened by internal drivers of deforestation and logging, especially if new roads and other transportation infrastructure are built as planned (Mosnier et al. 2014).

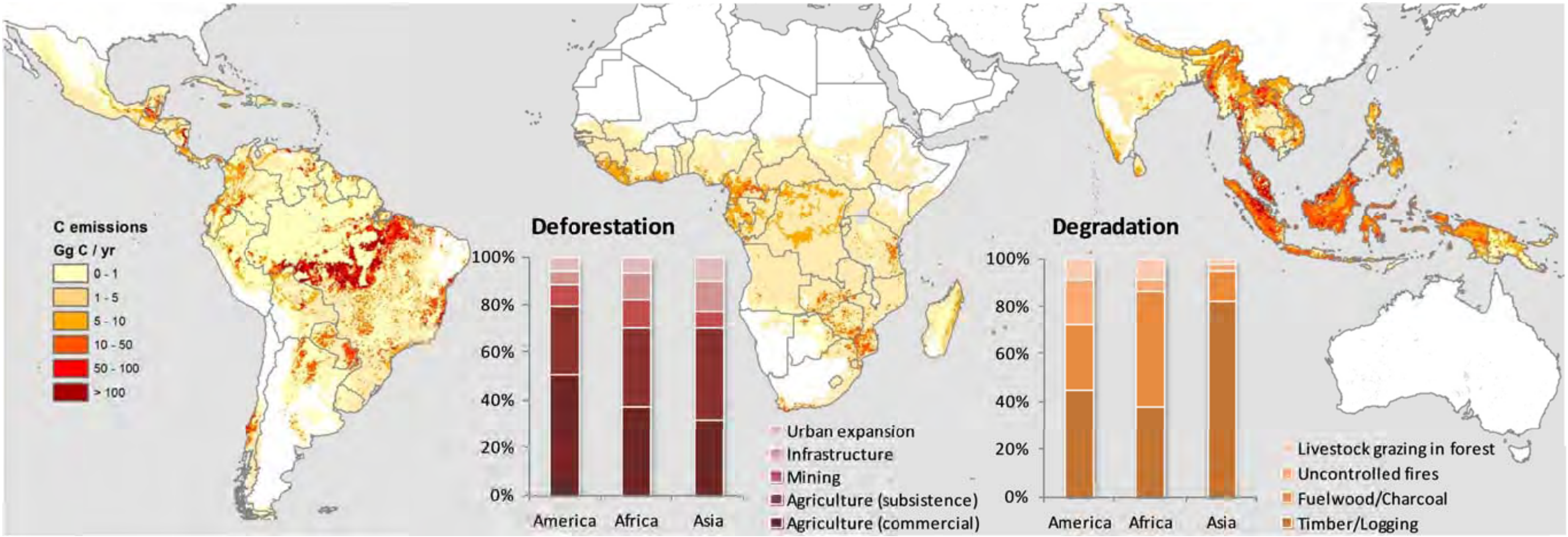

Figure 7. Annual tropical forest-based emissions (2000–2005) —data adapted from Harris et al. (2012) by Valerio Avitabile (Wageningen University). Bar charts show the relative importance of different drivers of deforestation and forest degradation in each continent (data from Hosonuma et al. 2012).

6.2 Projected rates of deforestation

Future deforestation rates are of course unknown, but the forest transition model is often used to give insight into common trends. The forest transition model describes the stereotypical forest cover changes associated with a country's development over time. Initially, countries have high forest cover (pre-transition). Deforestation rates are then high during the early and late-transition periods as land is cleared primarily for agriculture. Finally, there is a slight recovery in forest cover as less productive agricultural lands are abandoned (allowing for regeneration and succession to proceed) and land is actively replanted in the post-transition phase (Köthke et al. 2013). The majority of tropical and sub-tropical countries are in the 'early' or 'late transition' phases of the Forest Transition model, in which rapid deforestation occurs but rates decrease over time (Hosonuma et al. 2012). This may explain why deforestation rates have decreased slightly but remain high. Further, it suggests that rates will remain high in the near future. Agribusiness —especially producing soybeans, cattle, and palm oil for international markets— has been the leading driver of deforestation in South America and Asia (Figure 7). Commercial agriculture is the most prevalent driver of deforestation in the early transition phase and is an increasingly important driver of deforestation in recent times (Hosonuma et al. 2012). Thus far, deforestation in Africa is still dominated by subsistence farming, but this could change and increase rates of deforestation in the future. Many countries with the highest forest cover in the Congo Basin and western Amazon are still in the pre- and early-transition stages, indicating that large tracts of intact forest could be lost in the coming decades as globalization and industrial agriculture move into these areas (Hosonuma et al. 2012). Urban population growth is also expected in many tropical countries, which will also likely increase pressure on the surrounding forests (DeFries et al. 2010). Conversely, a small number tropical and sub-tropical countries are in the post-transition phase, where forest cover may be expected to increase, such as Chile, China, Costa Rica, India, Philippines, Rwanda, Uruguay, and Vietnam (Hosonuma et al. 2012).

Forest degradation dynamics also change with Forest Transition phases. In the late-transition phase, the importance of commercial logging decreases as timber resources are depleted while fuelwood collection and fires increase. The reverse occurs post-transition: economic development decreases the demand for fuelwood, commercial logging regains importance, and better forest management reduces the prevalence of fires (Hosonuma et al. 2012).

Policies, public awareness, and global economics will have a large impact on the future trends in deforestation. For example, policies in Brazil drove nearly a decade of decline in deforestation rates (Hansen et al. 2013), and a higher awareness of the value of mangroves may have led to the reduced destruction of these ecosystems recently (FAO 2007). Unfortunately, policies can also go the other way. A new policy in Brazil for example may reverse the long-running trend of reduced deforestation in Brazil: Deforestation in the Brazilian Amazon increased by 28 % from 2012 to 2013 (INPE-PROJETO PRODES 2014) perhaps because of a new Forest Code approved in 2012. On an international scale, globalization and further trade liberalization may increase tropical deforestation, GHG emissions, and other environmental degradation (Schmitz et al. 2012).

7. Implications for action

7.1 To what extent is reducing forest-based emissions essential for preventing climate change?

Forests play a huge role in the global carbon cycle and offer large, cost-effective, and immediate options for climate change mitigation. Indeed, they are already a large part of climate change mitigation. Reducing deforestation and other forest-based emissions play a vital role in avoiding catastrophic climate change, though we also need to severely reduce other sources of CO_2, methane, nitrous oxide, and black carbon, as well. The IPCC asserts that forestry activities will be an important and cost-effective component in a global effort to mitigate climate change (Smith et al. 2014). Likewise, the Stern Review: The Economics of Climate Change recognizes that curbing deforestation is one of the key elements of climate change mitigation (Stern 2006). Three mitigation options in the forestry sector include: (i) reducing or preventing emissions (i.e., reducing/avoiding deforestation, practicing reduced impact logging and sustainable forest management), (ii) sequestration (e.g, reforestation, afforestation, and soil management), and (iii) reducing fossil fuels emissions by substituting biofuels and energy-intense materials for wood products. At high carbon prices ($US 100/ t CO_2eq), the forestry sector alone is estimated to contribute up to 13.8 Gt CO_2eq each year of economically viable mitigation (Smith et al. 2014). Reducing deforestation is very cost-effective and much less expensive than other means of reducing greenhouse gas emissions (Stern 2006). The economics of climate change mitigation options will be discussed in more detail in later papers, but it is important to note that forestry-related mitigation activities are far less sensitive to the price of carbon than many other sectors (Smith et al. 2014).

It is also important to recall the basic facts about forests and their role in the global carbon cycle. Tropical forests currently hold approximately 1470 Gt of carbon in living and decaying biomass and soils, which is nearly twice what has accumulated in the atmosphere since the industrial revolution (240 Gt C). This highlights both the importance of keeping this carbon stored in the forests and the catastrophic potential of these forests to release carbon if they are completely destroyed. Moreover, mature tropical forests sequester at least 1Gt of C/year, on average. If the opposing FOLU fluxes are considered separately —regrowth in recovering forests (1.2–1.7 Gt C/year sequestered) and gross deforestation (2.6–2.8 Gt C/year emitted)— tropical forests (including sequestration in intact forests) removed 22–26 % of total annual anthropogenic emissions in the 2000s (Table 1; Pan et al. 2011, Houghton 2013). If deforestation were stopped entirely, tropical forests would remove 25–35 % of all carbon emissions from fossil fuels and cement production, and the entire land sink would remove over half of anthropogenic emissions (Figure 6B). Finally, the absolute difference between forest emissions and sinks (4.8–5.6 Gt C/year in tropical forests (Table 1, Figure 6B) shows the potential of the forestry sector to both reduce emissions and enhance sequestration. This was reinforced in a recent study showing that stopping tropical deforestation and degradation, protecting regrowing forests, and reforesting lands not currently in use has the potential to sequester 3–5 Gt C/year from the atmosphere (Houghton 2013).

Forest-related climate mitigation activities not only improve the global C cycle, but can have other climate benefits as well as a number of non-climate co-benefits, such as conservation of biodiversity, water cycling and availability, increased food security, and promoting sustainable growth in developing countries. Reforestation and afforestation, for example, would not only sequester CO_2 but have the additional climate benefits of increasing evapotranspiration and cloud cover (Bala et al. 2007).

Box 4. FAQ 6. What is the relative effectiveness of protecting existing forests versus planting trees? How long does it take for a natural forest to be restored to the same level of carbon richness?

One of the main differences between the mitigation potential of protecting existing forests compared to planting new forests is the timeline upon which they offer climate benefits: avoiding deforestation immediately avoids GHG emissions, whereas regrowing trees sequester carbon over time (Figure 5).

Doing very simple calculations, it will take 35 to > 130 years, on average, to restore carbon stocks in aboveground living biomass to 132 t/ha† with constant growth rates of 1 to 3.8 t C/ ha/ year (Pan et al. 2011). Using IPCC Tier 1 factors (i.e., default values when no national or regional data is available), shows that aboveground biomass stocks can recover in anywhere between 40 and 231 years for natural forests and plantations can recover carbon stocks in aboveground living biomass in 13 to 56 years‡ (Table 2). However, these are very rough estimates and say nothing about other carbon pools, such as soil, roots, litter, or woody debris. Furthermore, the growth rates are likely to be overestimates, and the years to recovery therefore too low, if they are based on the first few decades of growth only. Recall that it can take over 100 years for mature forests to recover from selective logging (Huang and Asner 2010). Nonetheless, these results shed some light on forest growth dynamics. For example, the number of years to accumulate original carbon stocks in trees varies by continent, climate, and species. The values reported in Table 2 are averages among a range of outcomes: the actual rates and level of recovery will depend on many factors, such as the type and severity of disturbance, level of soil degradation, the seed source, climate, and other ecosystem and landscape dynamics, and human interventions.

Forest plantations grow markedly faster than natural regeneration but are also fundamentally different from natural forests. Growth rates are faster for a number of reasons: the inherent growth rates of species are important, but human interventions —such as planting, weed control, fertilizer application— also accelerate the rates and success of tree establishment, survival, and growth. However, most plantations are destined to be cut, so although the carbon gains are faster, the sequestration is only temporary (though the process can begin again if replanted; Figure 5). Secondly, the biodiversity and ecosystem services do not match those of native forests (See Box 2).

All new forest growth (be it natural regeneration, re/afforestation, or plantations) plays a vital role in restoring forest cover and sequestering carbon from the atmosphere on currently under-stocked or completely un-stocked land that was previously forested. Planted forest can also provide valuable wood products and protect natural forests from degradation and deforestation. In Nigeria, for example, eucalyptus is planted on land severely degraded by mining to provide fuelwood to the local population (Wimbush 1963).

Table 2. The average number of years for aboveground carbon stocks in live trees to reach those in intact tropical forests in each continent. See methods in footnote‡.

Forest type	Moist forests		Wet
Length dry season	Long	Short	
Continent	***Natural regeneration (years)***		
Africa	141	143	86
America	231	96	153
Asia & Oceania - Continental	127	70	127
Asia & Oceania - Insular	90	40	82
	Plantations* (years)		
Africa	21-31	13-30	15-41
America	18-42	18-36	54-56
Asia	19-39	35-36	14-19

**Plantation species reported:*
Africa: Eucalyptus, Pinus, others
Americas: Eucalyptus, Pinus, Tectona, others
Asia: Eucalyptus others

†Methods: Mean C density in live biomass was estimated at 163.9 t/ha in intact tropical forests (282.5 t C/ha in all C pools × total stock of 228.2 Gt C in live biomass / total stock of 393.3 t C in all forest carbon pools) (Pan et al. 2011). Using the IPCC root/shoot-ratio of 0.24 for primary tropical moist forests, aboveground carbon stocks in living biomass was estimated at 132.2 t C/ha (IPCC 2003). Wet forests are defined as having a dry season of ≤ 3 dry months/year, and moist forests have 3–5 dry months/year.

‡ Methods: By the same methods as above, mean C density in aboveground living biomass was estimated at 125.0, 131.7, and 136.8 t C/ha in African, SE Asian, and American intact tropical forests, respectively. Average annual increment of natural regeneration and forest plantations were taken from Table 3A.1.5 and 3A.1.6 IPCC (2003), and biomass was converted to carbon using the conversion factor of 0.47 (IPCC 2006).

7.2 To what extent are emission reductions from forests time-sensitive?

The IPCC recommends aiming for an atmospheric concentration of 450 ppm CO_2eq by 2100 for a likely chance of limiting the mean global temperature rise to 2 °C (3.6 °F) over pre-industrial mean temperature. This would require large and immediate reductions in GHG emissions by changing energy systems and land use (Edenhofer et al. 2014). Because we are likely to overshoot atmospheric concentration of 450 ppm CO_2eq, plants will be necessary to ultimately reduce CO_2 from the atmosphere (e.g., afforestation and bio-energy with carbon capture and storage). An advantage of re/afforestation to remove CO_2 from the atmosphere is that trees are not experimental and the technical capacity to plant and maintain trees is immediately available (unlike carbon dioxide removal or carbon capture and storage technologies) (Ciais et al. 2013).

Action on multiple fronts is needed immediately in order to achieve 2 °C temperature targets. Delaying action only puts more pressure on drastic changes in the future and lessens our overall chances of avoiding dangerous climatic changes (Edenhofer et al. 2014). The *rate* of climate change is also important, and mitigation also buys us time to adapt (Edenhofer et al. 2014). Many FOLU mitigation strategies can and should be implemented immediately, such as reducing deforestation, increasing afforestation efforts, and improving fire management.

In general, CO_2 emissions reductions from AFOLU play a relatively large role in total CO_2 emissions in the short term (i.e., until 2030) and reduce in importance over the long-term (Smith et al. 2014). The IPCC warns that forest and land use mitigation options today may not be available in the future, and the ability of forests to serve as a sink, not a source, of CO_2 depends on climate change itself, as well as other environmental stresses and disturbances (Edenhofer et al. 2014) (see Box 5). We should, therefore, utilize this natural resource and enhance its capacity as a solution for immediate action.

BOX 5. Climate change feedbacks

FAQ 7. What is the expected impact of climate change itself on emissions from tropical forests?

Ecosystem models predict that climate change will have an overall negative effect on tropical forests and their carbon balance, but more recent models predict that the threat of large-scale forest dieback is not as high as previously estimated. Fortunately, tropical forests may be more resilient to climatic changes than previously thought, and the risks of some dieback are moderate in South America and less in Africa and Asia (Huntingford et al. 2013).

Nonetheless, forests are threatened by climate change, and models consistently predict a positive feedback between the carbon cycle and climate (Le Quéré et al. 2013, Cox et al. 2013, Davidson et al. 2012), where 'positive' means self-perpetuating. Forests are currently net carbon sinks because growth and recruitment (new trees) exceed mortality. However, several mechanisms (especially related to climate change) could cause changes in the relative rates of these processes, thereby making tropical forests carbon neutral or net *sources* of carbon (Phillips and Lewis 2014).

It is difficult to predict exactly how forests will respond because key processes, such as disturbances (e.g., fire, logging, pests), ecosystem dynamics, nutrient dynamics, and peatland responses to climate change are all very difficult to understand and model. Rising temperatures increase respiration and may reduce photosynthesis (Lloyd and Farquhar 2008). Higher atmospheric CO_2 concentrations have thus far stimulated tree growth, but other nutrients and resources are expected to become limiting (Lewis et al. 2004). Precipitation patterns are expected to change as the climate changes, and moisture stress is likely to increase across the tropics (Tsonis et al. 2005). Tropical forests are sensitive to moisture stress, as seen during the 2005 (Phillips et al. 2009) and 2010 (Lewis et al. 2011) Amazonian droughts, where increased mortality and reduced growth caused these forests to be a net source of CO_2. Drought also increases forests' vulnerability to fire (Nepstad et al. 2004). Several studies show that Amazonian forests are fairly resilient to moderate droughts, but the combined effects of deforestation, fire, and drought are likely to alter precipitation cycles and eventually reduce carbon stocks (Davidson et al. 2012). Increased severity and frequency of droughts are also likely to cause large GHG emissions from peatlands (Fenner and Freeman 2011). Methane emissions from wetlands, especially in the tropics, are projected to increase in response to elevated temperatures and CO_2 concentrations (van

Groenigen et al. 2011).

The future of forest carbon fluxes is therefore uncertain. Fortunately, most models predict that forests will continue to be net carbon sinks, though they will store less and less as temperatures rise (Ciais et al. 2013). Indeed, the tropical carbon sink already appears to be shrinking (Pan et al. 2011). It is important to note that FOLU activities themselves may also have a role in the risk of forest dieback by altering both global and local climatic conditions: deforestation itself has many climate-vegetation feedbacks —e.g., altering albedo, surface temperatures, soil moisture, evapotransipration, cloud formation, and water and nutrient cycles (Strengers et al. 2010)— that may leave forests more vulnerable to dieback (Davidson et al. 2012). The southern Amazon, which has experienced high levels of deforestation and land use change, is already showing changes in water and carbon cycles (Davidson et al. 2012),

7.3 Priority geographies for action

The greatest mitigation potential from forests varies by region, and interventions should be planned accordingly, linking drivers of deforestation and degradation in each location to forestry and land use policies and interventions. Within the tropics, the economic mitigation potential of forestry is largest in Latin America, followed by Asia and Africa. In both Latin America and Africa, the mitigation potential of the forestry sector is larger than all other AFOLU activities combined. Within forestry, reducing deforestation has the greatest potential in Latin America and Africa, whereas improving forest management has a larger potential to reduce emissions than arresting deforestation in Asia and outside the tropics. Forests in many countries in the Congo Basin and Central Africa are relatively pristine but may be on the brink of rapid destruction, meaning that a timely and comprehensive REDD+ program could spare these forests from large-scale deforestation and degradation (Mosnier et al. 2014). In Indonesia, halting drainage and burning of peatlands has the greatest potential to reduce emissions (Verchot et al. 2010). The relative contribution of re/afforestation is more equal across all three tropical continents (Smith et al. 2014).

For effective climate change mitigation, we need a *coordinated* and *comprehensive* land-mitigation policy among regions and forestry activities. Staggered policies and implementation could lead to leakage, thereby lessening the intended reductions in deforestation and C emissions (Rose and Sohngen 2011, Calvin et al. 2009, Murray 2008). REDD+ has a great potential to be such a comprehensive land-management and climate change mitigation strategy —focusing on Reducing Emissions from Deforestation and forest Degradation (REDD); and the '+' includes conservation of forest carbon stocks, sustainable forest management, and enhancement of forest carbon stocks. REDD+ is a large-scale climate change mitigation mechanism with key initiatives from the United Nations (UN-REDD Programme) and the World Bank (Forest Carbon Partnership Facility (FCPF) and Forest Investment Program (FIP)).

Many countries are already engaging in REDD+, and it is important to keep this momentum going. Encouragingly, most countries in Latin America, Southeast Asia, and highly forested areas in Africa have chosen to participate in REDD+ (Figure 8). Of the 43 countries, 10 have driver-specific interventions, while the remaining 33 have interventions without linkage to specific drivers (Salvini et al. in press). More support is likely needed to increase the capacity of many of these countries to develop, implement, and monitor effective REDD+ interventions, and to maintain safeguards against perverse social and environmental outcomes.

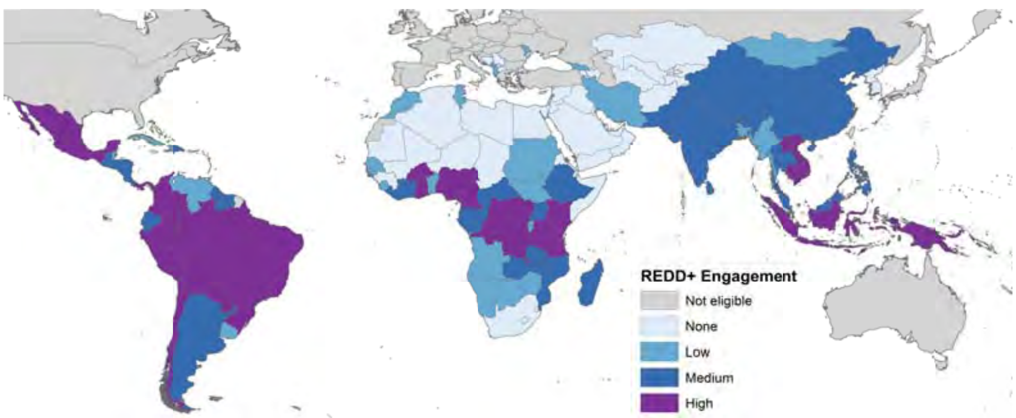

Figure 8. Level of REDD+ engagement by country. REDD+ engagement is determined by national engagement in international REDD+ initiatives (UN-REDD, FCPF, GEF, GCF), engagement at the sub-national level through project development (number of projects), and funding acquisition (Climate Funds Update). Levels of engagement in some initiatives (UN-REDD, FCPF) were taken into account and more weighting given to those countries that have progressed further through the process. Credit: Sarah Carter (CIFOR, Wageningen University).

8. Conclusions and recommendations

Forests and climate change are intrinsically linked. Forests loom large in the terrestrial carbon cycle, and they can and should be utilized as part of the solution for immediate climate change mitigation action. Tropical forests have the highest carbon densities in the world but are also subjected to the highest deforestation rates, thereby accounting for almost all net emissions from land use, land use change, and forestry. Tropical forests store more than double the amount of carbon than all the anthropogenic carbon emissions that have accumulated in the atmosphere thus far. Moreover, these forests sequester 2.2–2.7 Gt of carbon each year in mature forests, forests regenerating after deforestation, and forest regrowth after logging (Pan et al. 2011, Houghton 2013), thereby removing 22–26 % of total annual anthropogenic carbon emissions from the atmosphere since the 1990s. REDD+ activities —curbing tropical deforestation and degradation, protecting regrowing forests, and actively planting trees (reforestation and afforestation)— have the potential to reduce emissions and increase sequestration from the atmosphere by up to 5 Gt of carbon each year (Houghton 2013), over half of annual anthropogenic carbon emissions.

Compared to other mitigation strategies, reducing emissions from tropical deforestation and degradation is a cost-effective option and the most viable strategy in the land sector. Reducing CO_2 emissions from forestry plays a relatively large role in total CO_2 emissions in the short term and buys us time to develop other, more long-term mitigation and adaptation strategies. Unlike carbon dioxide removal technologies, trees (planted or left undisturbed) can *and already do* remove carbon from the atmosphere naturally. Likewise, forests and the rest of the terrestrial land sink are the only safe reservoir for excess CO_2, unlike the atmosphere where it causes warming and the oceans where it causes acidification. Unfortunately, these forests —and their vital role in the carbon cycle and climate change mitigation— are threatened by climate change itself and could become a net source of CO_2 if climate change continues unabated (Box 5).

The time to act is now, and we need coordinated and comprehensive action. The majority of tropical countries with high forest cover are already engaging in REDD+, and it is important to keep the process moving forward. The drastic reduction in deforestation in Brazil, as well as the rise in afforestation in China, demonstrate how forest-related policies, land planning, and public awareness can have a significant impact on forest cover and the global carbon cycle.

For effective climate change mitigation, it is vitally important to link drivers of deforestation and degradation in each location to REDD+ interventions and forestry and land use policies. REDD+ safeguards must also be considered to account for perverse social, economic, and environmental outcomes. By addressing the underlying drivers of deforestation and forest degradation, REDD+ can help achieve immediate climate change mitigation, as well as a number of social, economic, and environmental benefits by improving land management and maintaining tropical forests.

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