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WORKING PAPER

ENDING TROPICAL DEFORESTATION: A STOCK-TAKE OF PROGRESS AND CHALLENGES

TROPICAL FORESTS AND CLIMATE CHANGE: THE LATEST SCIENCE

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KEY POINTS

- **Forests can be used to reduce greenhouse gases in two ways: by avoiding emissions from deforestation and degradation, and by letting them grow and sequester more carbon.** Both must be encouraged and incentivized to realize a forest sector that is increasingly net carbon negative.
- **Conservation, restoration, and improved management of tropical forests, mangroves, and peatlands could provide 23 percent of cost-effective mitigation action needed by 2030 to limit global warming to 2°C.** This is nearly two-thirds of the combined cost-effective mitigation potential of forests and other natural climate solutions in the land sector globally.
- **The true influence of tropical deforestation on climate is even larger when noncarbon impacts are considered.** Taking multiple factors into account, modeling studies strongly agree that continental-scale deforestation in any of the three major tropical forest zones would leave climates in those areas warmer and drier. In deforested areas, local temperatures rise, and deforestation-driven disruptions to the water cycle can threaten agriculture both locally and half a world away.

CONTENTS

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THE ISSUE

Recent analysis shows that forests are essential to meeting the goals of the Paris Agreement, and contribute to climate stability through multiple pathways across local to global scales. Reducing emissions from deforestation, enhancing the role of forests as carbon sinks through restoration, and recognizing the noncarbon pathways through which forests affect the climate are all elements of a cost-effective solution to climate change. Yet forests' potential for mitigation does not receive commensurate international political attention or financial support.

WHY THE LATEST SCIENCE IS IMPORTANT TO FORESTS, CLIMATE CHANGE, AND DEVELOPMENT

Under the Paris Agreement, nations have committed to holding the increase in global average temperature to well below 2°C above pre-industrial levels, to strive to limit the increase to 1.5°C, and to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century. Balance requires either zero greenhouse gas emissions, which is unlikely, or negative emissions at a scale equal to positive emissions. Most global climate modeling scenarios compatible with a 2 or 1.5°C goal depend on some level of carbon removals (or "negative emissions") to balance remaining emissions.

In the coming decades, climate change will bring hotter temperatures, rising seas, and shifting rainfall patterns. In this future, many of the services provided by tropical forests will become even more important both for climate mitigation and climate adaptation (Seymour and Busch 2016). Reducing and reversing forest loss can also contribute significantly to sustainable development; forests can provide food, fuel, timber, and medicines, as well as cultural services and soil protection. Healthy forest landscapes contribute to healthy communities through disease control and water and air quality; to community safety through landslide and flood protection; to energy security through water and fuelwood; to food security through crop productivity and fish habitat; and to income and livelihoods through ecotourism and sustainable wood harvests (Brandon 2014; Mullan 2014).

PROGRESS IN THE LATEST SCIENCE

Tropical Forests and Climate Change Mitigation: 8 Percent of the Problem, 23 Percent of the Solution

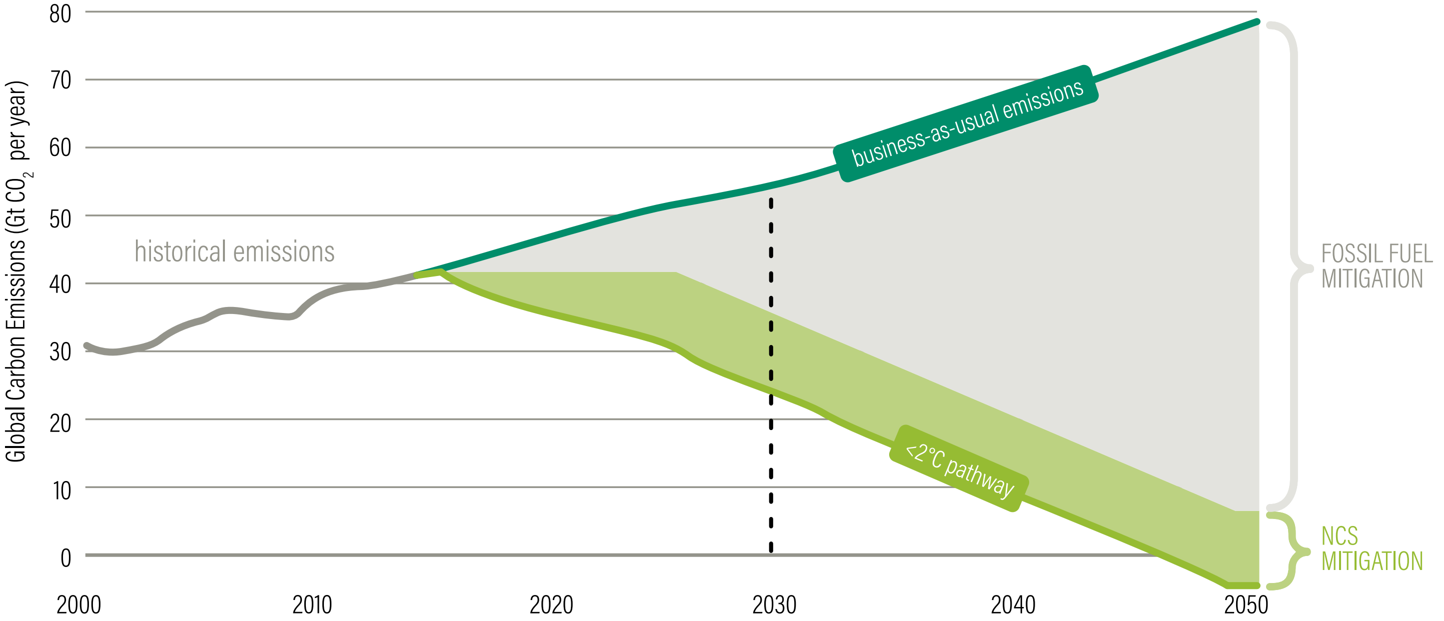
Managing the global carbon cycle over the next several decades will be critical to avoid excessive buildup of carbon dioxide in the atmosphere. Carbon emissions from fossil fuels far exceed those from deforestation and other land use changes in global inventories (Le Quéré et al. 2016), a fact that can sometimes lead both reporters and policymakers to falsely believe that forests play a relatively minor role in climate change mitigation.

This confusion stems in part from the scientific community's emphasis on reporting the net balance between forest-related emissions and removals; carbon sequestration by regrowing tropical forests is subtracted from emissions caused by tropical deforestation. The net balance of these two terms represents about 8 percent of total anthropogenic emissions (Seymour and Busch 2016).[1] However, this net accounting approach is deceptive to a global community trying to understand opportunities for climate change mitigation, because mitigation opportunities in tropical forests don't "cancel out" the same way they do in terms of atmospheric carbon accounting. While the net contribution of tropical forests to the climate problem involves subtraction (emissions minus sinks), the size of the tropical forest solution is additive (avoided emissions plus continued and enhanced sinks). Just as one's money in a bank account can increase over time both by making deposits and reducing withdrawals, carbon storage on land can increase over time both by increasing carbon sequestration through restoring and replanting forests and by reducing emissions through slowing and stopping deforestation.[2] Thus even though tropical forests represent only 8 percent of total emissions on a *net* basis, the mitigation potential from continuing and expanding forest growth and halting deforestation *and* degradation in the tropics at the same time adds up to much more.

How much more? Recent research by Griscom et al. (2017) suggests that globally, the land sector[3] an deliver 11.3 Gt CO_2 of climate mitigation per year in 2030, or 37 percent of the total needed between now and 2030 to limit warming to below 2°C (see Figure 1A). Of this total, nearly two-thirds (7.1 Gt CO_2) can be delivered through the conservation, restoration, and improved management of tropical forests, mangroves, and peatlands (see Figure 1B). This means that although they represent only 8 percent of emissions on a net basis, tropical forests and wetlands can deliver 23 percent of the total mitigation needed between now and 2030. At less than US$100 per ton of CO_2, these opportunities are cost effective and compare favorably with cost estimates for emerging but as yet unproven technologies, most notably bioenergy with carbon capture and storage (BECCS),[4] which ranges from approximately $40 to over $1,000/ton CO_2 (Griscom et al. 2017).

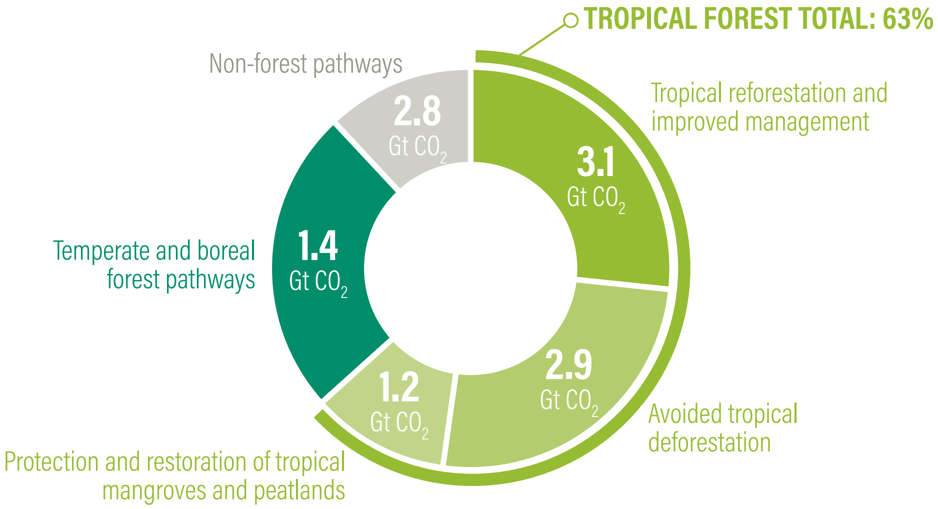
Figure 1 | **The Importance of Forests for Climate Change Mitigation**

1A | Contribution of Natural Climate Solutions to < 2°C pathway



Note: Potential contribution of the land sector in cost-effectively stabilizing warming to below 2°C. The green area shows the aggregate of 20 pathways that offer 37 percent of the needed carbon mitigation through 2030, 29 percent at year 2030, 20 percent through 2050, and 9 percent through 2100.
Source: Reproduced from Griscom et al. 2017 Figure 2.

1B | Tropical forests can deliver nearly two-thirds of the land sector's cost-effective mitigation potential by 2030



Note: Most of the total land-based mitigation opportunity comes from tropical forests.
Source: Data from Griscom et al. 2017, Supplementary Information Table S4.

Realizing the scenario illustrated in Figure 1A will require substantial effort from all countries to reach both fossil fuel and land-based mitigation targets. As part of the Paris Agreement, countries provided nationally determined contributions (NDCs) that indicate what climate actions they plan to take up to 2030. Most NDCs included the land sector in their mitigation plan, but less than a quarter offered specifics regarding what their land sector contributions would be (Forsell et al. 2016). Using a range of information and several assumptions to address these uncertainties, Grassi et al. (2017) estimated that if countries are fully successful in achieving their NDCs, by 2030 the world's managed forests will collectively reduce atmospheric greenhouse gases by 3.8 Gt CO_2, or more than Russia emits today (Harris and Lee 2017). Thus, a portion of Griscom et al.'s (2017) total land-based mitigation of 11.3 Gt CO_2eq/yr has already been included in current NDCs. However, NDCs still fall short by about 11–14 Gt CO_2 of the total mitigation needed to keep 2030 emissions in line with a 2°C scenario, so tropical forests—and the land sector more broadly—could contribute significantly and cost effectively to the increased (but not yet realized) ambition needed by NDCs to achieve Paris goals.

Griscom et al.'s (2017) research is corroborated by other research (e.g., Roe et al. 2017; Smith et al. 2014), highlighting that forest-based mitigation strategies—through pathways of both reducing emissions and enhancing removals—present large and cost-effective mitigation solutions, without which the Paris Agreement's temperature goals will be out of reach. But to date, land-based mitigation efforts have received *less than 3 percent* of all climate mitigation dollars (Buchner et al. 2015; Climate Focus 2017).

Beyond Carbon: Tropical Deforestation Influences the Global Climate Through Multiple Forcings

When thinking about global climate change, most of us think about carbon dioxide (CO_2), the main greenhouse gas emitted into the atmosphere because of human activities. But CO_2 is just one of many greenhouse gases in the atmosphere that influence what is known as "radiative forcing" (Myhre et al. 2013). Radiant energy arrives at our planet from the sun and escapes from Earth back to the cold of outer space. Along the way, surfaces on the Earth and gases in its atmosphere absorb and reflect some of this solar energy.[5] The balance between absorbed and reflected energy is what determines the global temperature, so anything that changes the energy balance between Earth and space impacts the global climate system.

Box 1 | The Role of Tropical Peatlands and Mangroves

Although limited in land area compared to other ecosystems, both tropical mangroves and tropical peatlands play a disproportionately large role in climate mitigation. Tropical mangroves also play a role in climate adaptation, protecting coastlines from storm surges and sea level rise and providing flood prevention amidst the extreme rainfall expected to increase with a warming climate. Tropical peatlands provide critical buffers against flooding during the wet season and insurance against drought in the dry season.

One of the most effective areas for climate mitigation in the land sector is protecting and restoring tropical peatlands, especially in Indonesia where they are a popular target for oil palm expansion. When peatlands are drained to prepare new land for planting, carbon in the soil is released. Indonesia's peatlands store 75 Gt C, about 30 percent more than all of Indonesia's forest biomass[a] and about 10 percent of all carbon in the atmosphere. Globally, peatland drainage accounts for one-third of cropland emissions despite producing just 1 percent of the world's food.[b] Each hectare of tropical peat drained for plantation development emits an average of 55 metric tons of carbon dioxide every year,[c] roughly equivalent to burning more than 6,000 gallons of gasoline. Drainage also makes peatlands more susceptible to fire, which can lead to uncontrollable outbreaks as seen in 2015. One way to achieve large and immediate emission reductions in the land sector is to support implementation of Indonesia's ban on peatland burning and its new and strengthened law to conserve and restore its peatlands.

Sources: a. Murdiyarso et al. 2011; b. Carlson et al. 2017; c. IPCC 2014b.

Positive radiative forcing happens when incoming energy exceeds outgoing energy, warming the global climate system. Negative forcing happens when outgoing energy exceeds incoming energy, cooling the global climate system. The overall net radiation balance is influenced by many factors, including changes in the concentration of greenhouse gases, the reflectivity of clouds and other gases in the atmosphere, and the absorption of energy by land and ocean surfaces. These various radiative forcing impacts are quantified at a common location (the top of the atmosphere) and in a common unit (watts per square meter of the Earth's surface).

The world's forests are continually immersed in this flow of energy, and thus play a complex and critical role in the global energy balance (see Figure 2). Clearing tropical forests and draining carbon-rich peatlands for agriculture shift carbon from the land to the atmosphere, increasing atmospheric CO_2 concentrations, which contributes to a positive radiative forcing, or warming, on the global climate system through the greenhouse effect. Fire—often used in the tropics to quickly clear forest land of remaining vegetation before it is cultivated with a new agricultural crop—also releases other greenhouse gases besides CO_2, notably methane (CH_4) and nitrous oxide (N_2O). In contrast, reforestation removes CO_2 from the atmosphere and thus contributes to a global cooling effect.

Changes in tropical forest cover also influence radiative forcing through more indirect pathways. Forests naturally release a wide range of chemical compounds like isoprene (biogenic volatile organic compounds, or BVOCs), which mix with various other atmospheric gases and lead to both positive and negative radiative forcing. On the positive (warming) side, BVOCs produced by forests react rapidly with atmospheric oxygen, leading to higher concentrations of the greenhouse gases methane and ozone (O_3). On the negative (cooling) side, BVOCs interact with other atmospheric molecules to produce aerosol particles, which scatter sunlight as well as increase cloud brightness by shifting the density and altitude of clouds. When tropical forests are cleared, fewer BVOCs enter the atmosphere. Through model simulations, Scott et al. (2018) showed that after tropical deforestation, the positive radiative forcing (warming) caused by a loss of reflective aerosols was larger than the cooling caused by a reduction in methane and ozone concentrations. In sum, lower BVOC emissions after deforestation leads to a net warming effect.

The presence or absence of forest cover also has a strong impact on surface albedo, or the reflectivity of the Earth's surface to solar energy. Dark green forest cover has a low albedo and absorbs more sunlight than relatively brighter crops or grasslands, which reflect more sunlight. Deforestation in the tropics thus contributes to a negative radiative forcing, or global cooling, through changes to surface albedo (Myhre et al. 2013).

Researchers have made significant progress over the past several years in understanding the radiative forcing impacts of forest cover loss, but it remains unclear whether warming from reduced BVOCs is greater or less than the cooling from increased surface albedo. For example, a simulation of tropical deforestation through 2100 by Ward and Mahowald (2015) finds that the warming from BVOCs dominates, resulting in a total radiative forcing that is nearly 20 percent higher than the CO_2-only impact. A simulation of tropical deforestation by Scott et al. (2018) shows the reverse—a much smaller BVOC impact than albedo effect, resulting in a net radiative forcing about 12 percent lower than the expected CO_2-only impact. In either case, though, tropical deforestation leads to an unambiguous net positive radiative forcing dominated by the CO_2 effect, which is more than three times larger than the additional warming from reductions in BVOCs, and seven or more times larger than surface albedo-induced cooling.

The analyses summarized above accounted only for the impacts of reduced tree cover, but not the impacts of a shift in land use from forests into agricultural land. When researchers examine the combined radiative forcing impact of the loss of forest cover *together* with the emissions from agriculture in areas that were previously forest, the impact is clearly larger than the CO_2 effect alone. From this perspective, Ward et al. (2014) conclude that land-based emissions are relatively more important compared to fossil emissions than previously thought: Land use and land cover change since 1850 is estimated to be the source of 40 percent of present-day total anthropogenic warming. By 2100, Mahowald et al. (2017) suggest that tropical deforestation would likely result in 1.5°C of warming even if all other sources of anthropogenic emissions were to immediately cease. Therefore, halting tropical deforestation is critical to holding the average increase in global temperature to below 2°C.

Beyond Global: Tropical Deforestation Leads to Hotter, Drier Conditions at Local to Continental Scales

As mentioned above, radiative forcing represents the balance of Earth's incoming and outgoing energy at the top of the atmosphere. But what happens in between? Energy from the sun drives the global climate, and solar heat energy is distributed across Earth's surface through moving fluids—air and water. This movement is caused by the tendency of warmer, less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in a transfer of heat. The global movement of air and water to distribute heat energy causes Earth's predominant wind patterns and ocean currents, while local movement of air and water to distribute heat energy determine local weather and climate.

Forests play a significant role in shaping the climate at all scales by driving movement of air, water, and heat through evaporation and transpiration. Regionally, large intact forests along the coasts of continents can create low pressure weather systems, generating rain and prevailing winds that can carry moist air from oceans deep into the interior of continents (Sheil and Murdiyarso 2009). Through the process of evapotranspiration, trees pump water from their roots out through their leaves as water vapor, humidifying the air and causing surface cooling. Forests have more leaf surface area and deeper roots than grasslands or croplands, and thus cycle more water. A single tree transpiring hundreds of liters of water per day can cause local surface cooling equivalent to 70 kWh for every 100 liters—energy sufficient to power two household central air conditioners per day (Ellison et al. 2017). Remove the trees, and the system can't recycle as much water as quickly, leading to local flooding, soil erosion, and even local and downwind droughts (Ellison et al. 2017). At high elevations, loss of forest cover slows the interception of fog and cloud droplets, reducing water available to these ecosystems (Ellison et al. 2017). Smoke and haze from forest and peat fires also disrupt rainfall patterns by scattering sunlight, slowing the uplift of water vapor into the atmosphere and altering atmospheric circulation (Ellison et al. 2017). These impacts of changes in tropical forest cover on water and heat cycling extend well beyond the tropical regions themselves through "teleconnections," where climate anomalies are related to each other over large distances spanning thousands of kilometers. While models differ in the precise location and scale of transcontinental impacts of tropical deforestation through teleconnections, changes in rainfall driven by tropical deforestation combined with warmer temperatures could pose a substantial risk to agriculture in key breadbaskets halfway around the world in parts of the U.S., India, and China (Lawrence and Vandecar 2015).

Forests also impact the texture, or roughness, of the Earth's surface, which in turn influences how and where heat and water are distributed. The physical configuration of trees interacts with passing wind currents to slow horizontal air streams and increase the vertical transfer of air through turbulent mixing. Remove the forests, and faster winds accelerate evaporation and dry out the land surface (Lawrence and Vandecar 2015). These surface roughness effects can influence rainfall patterns in other more complex ways, and potentially increase condensation of water from fog and clouds. A loss of surface roughness with deforestation also increases near-surface temperatures (Bonan 2016).

Model simulations of these nonradiative forcing impacts of deforestation in the tropics show net local warming: Warming from loss of forest surface roughness and loss of evaporative cooling more than offset the cooling from increased albedo (Bonan 2008, 2016). In a study comparing air surface temperatures and satellite-observed tree cover loss between 2003 and 2012, Alkama and Cescatti (2016) found that deforested areas experienced significant and long-lasting increases in local air surface temperatures, with daily average and maximum temperatures increasing by about 1 and 2°C, respectively.

Modeling studies strongly agree that continental-scale deforestation in any of the three major tropical forest zones—the Amazon, Central Africa, and Southeast Asia—would leave the climates in those areas warmer and drier, with the largest effect in the Amazon: Complete deforestation would lead to regional warming of approximately 2°C and an estimated 15 percent drop in annual rainfall (Lawrence and Vandecar 2015). Effects of partial deforestation on regional rainfall are more mixed at intermediate scales in both models and observational studies, although both show changes in rainfall frequency, intensity, and seasonal distribution even when total rainfall projections are constant. These recent studies provide strong evidence that changes in tropical forest cover go well beyond global radiative forcing impacts, which are relatively long term; deforestation changes the radiative balance at the surface as well, causing locally stronger and more temporally immediate effects on temperature and precipitation at all scales.

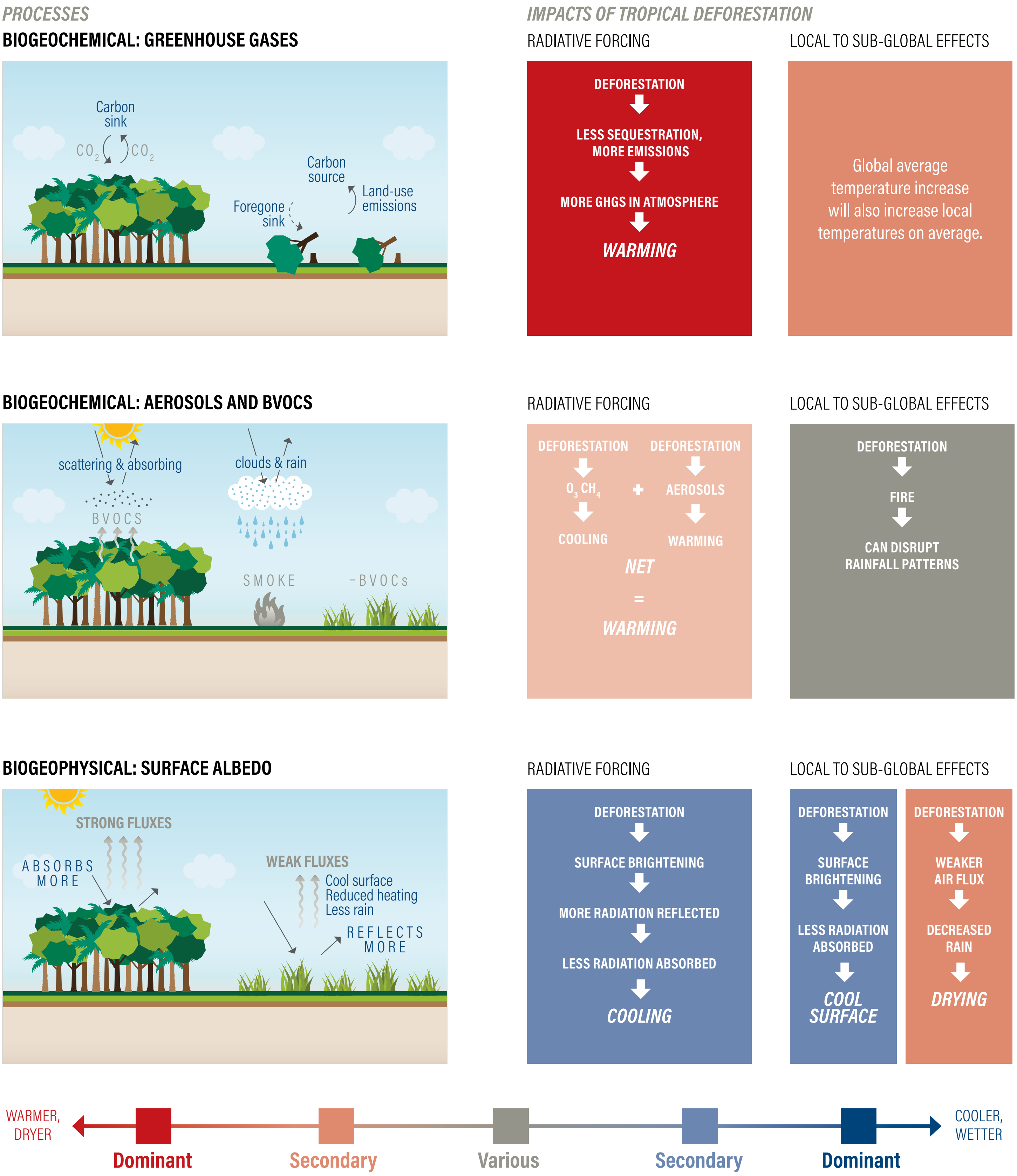
EVIDENCE GAPS AND AREAS OF CONTROVERSY

While recent science has advanced the understanding of forests' impact on climate through multiple processes and scales, several issues at the forest/climate nexus remain unresolved and controversial.

a. How well do we know carbon fluxes from tropical forests? Are tropical forests carbon neutral, a net source, or a net sink of CO_2?

Currently, conflicting lines of evidence are apparent regarding the net carbon balance of tropical forests. Bottom-up approaches suggest that average emissions from tropical land use change are roughly in balance with carbon removals by intact forests and secondary forest regrowth (Pan et al. 2011), while top-down atmospheric modeling studies indicate that tropical forests are a small net carbon sink due to a small fertilization effect from elevated atmospheric CO_2 concentrations (Schimel 2015). Most recently, Baccini et al. (2017) concluded that tropical forests are a relatively large net carbon source. To complicate matters further, these various scientific studies use different methodologies and definitions to track forest-related fluxes than national reports submitted by countries to the United Nations Framework Convention on Climate Change (UNFCCC)—making it challenging to monitor progress toward enhanced mitigation in the forest sector (Federici et al. 2017).

Figure 2 | **Climate Effects of Tropical Forest Loss**



PROCESSES

BIOGEOCHEMICAL: GREENHOUSE GASES

IMPACTS OF TROPICAL DEFORESTATION

RADIATIVE FORCING

DEFORESTATION
↓
LESS SEQUESTRATION, MORE EMISSIONS
↓
MORE GHGS IN ATMOSPHERE
↓
WARMING

LOCAL TO SUB-GLOBAL EFFECTS

Global average temperature increase will also increase local temperatures on average.

BIOGEOCHEMICAL: AEROSOLS AND BVOCS

RADIATIVE FORCING

DEFORESTATION
↓
O_3 CH_4
↓
COOLING

+

DEFORESTATION
↓
AEROSOLS
↓
WARMING

NET
=
WARMING

LOCAL TO SUB-GLOBAL EFFECTS

DEFORESTATION
↓
FIRE
↓
CAN DISRUPT RAINFALL PATTERNS

BIOGEOPHYSICAL: SURFACE ALBEDO

RADIATIVE FORCING

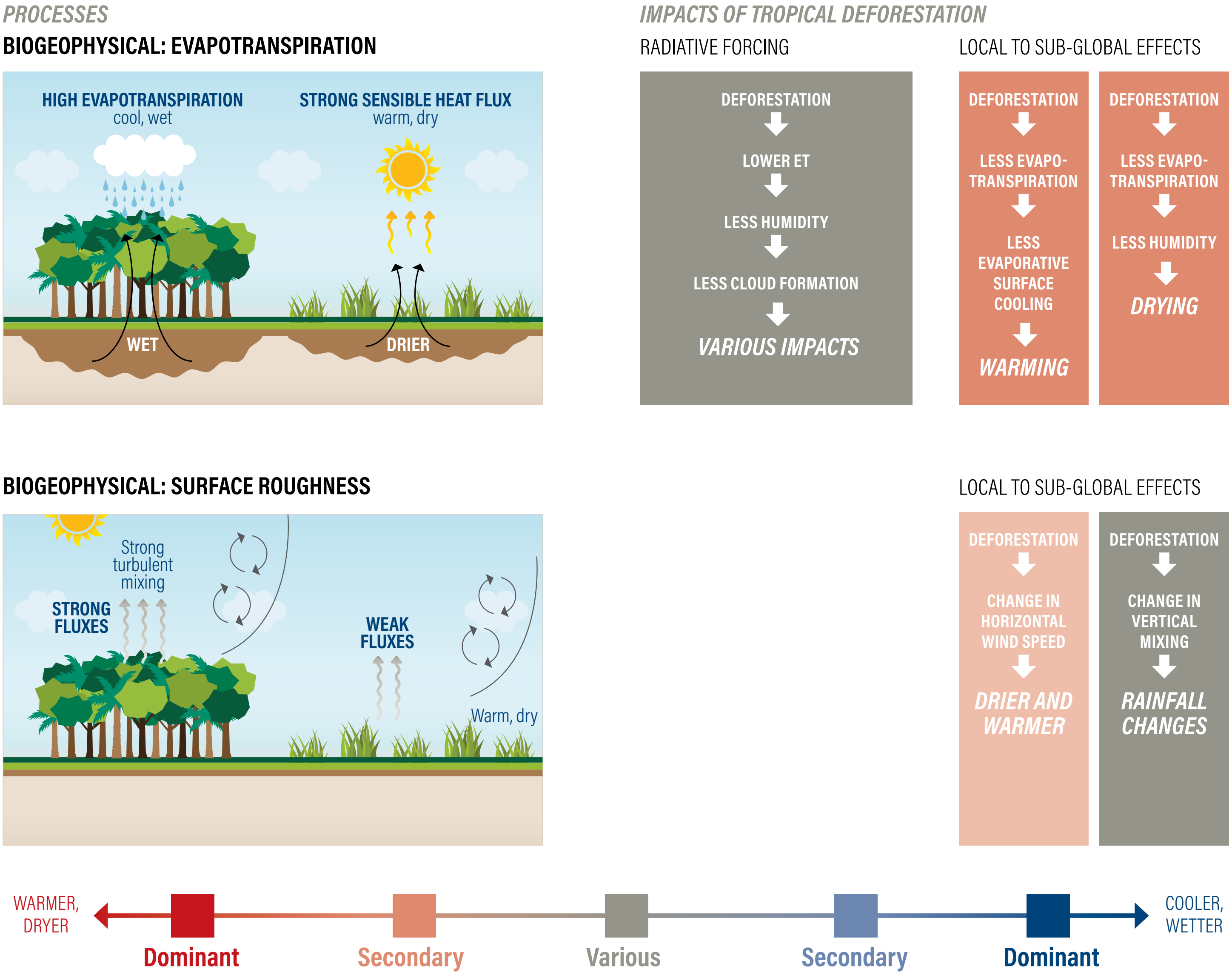
DEFORESTATION
↓
SURFACE BRIGHTENING
↓
MORE RADIATION REFLECTED
↓
LESS RADIATION ABSORBED
↓
COOLING

LOCAL TO SUB-GLOBAL EFFECTS

DEFORESTATION
↓
SURFACE BRIGHTENING
↓
LESS RADIATION ABSORBED
↓
COOL SURFACE

DEFORESTATION
↓
WEAKER AIR FLUX
↓
DECREASED RAIN
↓
DRYING

Figure 2 | **Climate Effects of Tropical Forest Loss (continued)**



Source: Process infographics adapted from Bonan (2016), Figure 2.

Although scientists will continue to refine their estimates, carbon fluxes in the land sector will remain difficult to measure with certainty. The scientific community and national governments should aim to achieve greater transparency and comparability on land-based carbon fluxes, but the definitive answer to the net carbon balance question for tropical forests is somewhat meaningless from a current climate policy standpoint. If tropical forests are in fact net sinks or in carbon balance, this is overwhelmingly due to the "background" sequestration occurring within unmanaged forest lands that are not accounted for under the UNFCCC.

Tropical managed forests that *are* included under the UNFCCC accounting framework are unambiguously a carbon source (Pan et al. 2011), and require proactive mitigation. Large mitigation opportunities are present both in terms of avoiding emissions from tropical deforestation and peatland impacts, and increasing sinks elsewhere in the tropics through reforestation. Arriving at net zero emissions across all sectors is the aspirational mid-century goal of the Paris Agreement, but this can only be realized if managed tropical forests become increasingly net negative.

b. Will tropical forest conservation and restoration compete with the need to increase food and fuel in the future? How feasible are these mitigation opportunities?

Achieving the full extent of climate mitigation that is possible through avoided deforestation, tropical reforestation, and peatland conservation and restoration is somewhat at odds with the need to feed a growing global population; the overwhelming driver of tropical deforestation has been the expansion of agricultural lands for commodities such as beef, soy, and palm oil (Gibbs et al. 2010; Henders et al. 2015). To address these concerns, the potential mitigation estimates reported earlier reflect *only* the mitigation that does not interfere with meeting increasing human needs for food, fiber, and fuel; that does not negatively affect biodiversity; and that is cost effective (<\$100/tons CO_2eq). Without these safeguards and cost constraints in place, the *maximum* mitigation potential for tropical forest pathways (14–18 Gt CO_2eq/yr; Griscom et al. 2017; Houghton et al. 2015) is approximately twice the potential reported above (7.1 Gt CO_2eq/yr). Even after accounting for these various safeguards and cost constraints, halting tropical deforestation and increasing tropical forest cover through reforestation and improved forest management remain the largest opportunities for climate mitigation in the land sector.

Despite reforestation's large mitigation potential, there is substantial uncertainty around just how much of it will be possible. For example, the difference between the lower and upper bounds of Griscom et al.'s (2017) reforestation mitigation pathway is larger than the total annual emissions from both the U.S. *and* China. This range arises from uncertainty in both the land area available for reforestation, including uncertainty about whether shifting diets or intensification reduce demand for cattle grazing lands, and from variability in sequestration rates across different locations and forms of reforestation (e.g., natural regeneration, agroforestry, or plantations). The uncertainty around mitigation potential of avoided deforestation is much lower than for reforestation. However, the feasibility of both interventions (avoided deforestation and reforestation) may be limited by the fact that many tropical forest areas lack clear land tenure, which may present challenges to effective implementation.

Furthermore, most Intergovernmental Panel on Climate Change (IPCC) scenarios compatible with a 2 or 1.5°C goal depend on negative emissions, which are usually assumed to be the result of BECCS. IPCC models assume about 12 Gt of net CO_2 sequestration from BECCS by 2100, which would require 25 to 46 percent of the amount of arable and permanent cropland available globally (Smith et al. 2016). Such large-scale deployment of BECCS would exceed acceptable risk thresholds for a wide range of planetary boundaries for human perturbation of the Earth system (Heck et al. 2018), but some level of BECCS and other negative emission technologies will likely be needed in the future. More recent research provides scenarios with a reduced reliance on BECCS (Van Vuuren et al. 2018), but given a finite global land base, there is still considerable controversy about what level of BECCS could be done sustainably and what the implications are for other land-based carbon removal approaches such as reforestation.

Ultimately, the feasibility of implementing any climate mitigation strategy in any country will depend on each country's resources, political will, institutional capacity, and governance. Many tropical countries have already committed to conserving and restoring their forests to meet climate mitigation and adaptation goals, but their success and increased ambition over time will depend largely on their ability to mobilize adequate finance. These countries should be provided with the opportunity to follow through on their ambition by receiving commensurate international support and financial assistance.

c. Will forest-related mitigation opportunities eventually saturate and level off?

In Figure 1A, the time horizon for saturation of the tropical reforestation pathway after 2030 is approximately 25 years (Griscom et al. 2017), meaning that these enhanced carbon removals will taper off around 2060. In contrast, the carbon mitigation benefits of halting tropical deforestation and avoiding peat impacts would continue for as long as these landscapes are conserved, as would the nonradiative forcing local and regional climate benefits. Given the challenge of rapid transformational change in the energy sector to reach the magnitude of fossil fuel emission reductions required under any <2°C scenario, successful near-term climate mitigation in the land sector is particularly important as a bridge to carbon neutrality by mid-century.

CONCLUSIONS AND NEXT STEPS

While areas of debate remain, the most recent research on mitigation opportunities and the negative outcomes of tropical deforestation on climate send a very clear and unambiguous message: **Tropical forest loss is having a larger impact on the climate than has been commonly understood.** Deforestation contributes to warming and disrupts rainfall patterns at multiple scales. These changes will impact all of us, threatening agricultural productivity in the tropics and beyond. The global community can reduce tropical forest loss and emissions and pursue reforestation and restoration at scale, while simultaneously maintaining other native ecosystems and having enough land to feed the rising global population. Maintaining and restoring tropical forests and the water cycles they regulate will provide the greatest benefit to those most threatened by climate change: The rural poor in developing countries, who would experience fewer heat waves, a more stable water supply for agriculture, and all the additional development benefits forests provide.

There is of course a need for additional scientific research and analysis to address open questions and better inform climate policymakers, including:

- Aligning the scope of academic research on forest carbon fluxes with national inventories and NDCs to better inform policymakers about mitigation opportunities, with greater transparency from both sides on how various estimates are derived.

- Reducing uncertainty in the magnitude of potential forest mitigation potential, especially with respect to evaluating interactions and trade-offs between pursuing bioenergy pathways and other forest mitigation pathways such as reforestation.

- Revisiting the gap between maximum and cost-effective forest mitigation potential, which may be narrower than currently understood when positive returns on agricultural productivity, food security, and other ecosystem services are accounted for.

These gaps are trivial compared to the vast chasm that exists between the evidence base and the ambition for action in the land sector. Bridging this chasm will require advances in many areas: increases in financial support and incentives, governance and law enforcement, political will, improvements in agricultural productivity, land rights, and more. There are also opportunities at the science/policy interface to bring new information to the challenge, including:

- Focusing on the key opportunities ahead to bring new scientific evidence to bear more directly on the policy process regarding the critical role of tropical forests on climate. These include the cycle of UNFCCC Stocktakes and NDC updates, starting with the ongoing Talanoa Dialogue; the long-term climate strategies the UNFCCC has called for by 2020 (which seven countries have submitted to date); and IPCC reports, including the Special Report on Climate Change and Land to be released in late 2019, and the Sixth Assessment Report (AR6) process leading to the release of Working Group Reports in 2021.

- Growing ambition for land-based mitigation from the bottom up. Countries that consider themselves leaders on forests and climate should ensure that their own NDCs have included natural climate solutions to the greatest extent possible and are outlined at the level of detail they hope to see from other parties.

- Exploring opportunities to appropriately account for nonradiative forcing pathways by which forests affect climate, including potentially the definition of new protocols by the IPCC and/or the UNFCCC to measure and report on them.

ABBREVIATIONS

BECCS	bioenergy with carbon capture and storage
BVOC	biogenic volatile organic compound
ET	evapotranspiration
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NDC	nationally determined contribution

ENDNOTES

1. Smith et al. (2014), Figure 11.8 shows a consistent estimate of 4.1 Gt CO_2/yr net emissions from tropical forests from 2000 to 2007, from Pan et al. (2011), which finds 10.3 Gt CO_2/yr emissions from tropical gross deforestation and -6.2 Gt CO_2/yr of uptake from tropical regrowth forests; and from Baccini et al. (2012), which estimates a gross source of 8.4 Gt CO_2/yr of emissions from deforestation, soils, industrial logging, fuelwood harvest, and shifting cultivation, and 4.3 Gt CO_2/yr of uptake from industrial logging, fuelwood harvest, and shifting cultivation recovery and reforestation. Seymour and Busch (2016) compare this 4.1 Gt CO_2/yr of net tropical forest emissions to 49 Gt CO_2eq/yr of total anthropogenic GHG emissions for 2010, from Figure SPM.1 of IPCC (2014a).

2. The analogy can be extended further. Forests are, in fact, an interest-bearing account: Mature and intact forest landscapes continue to sequester carbon over very long periods even with no new deposits from expanding forest area. Contrary to previous assumptions that mature forests are net carbon neutral, recent research on every tropical continent (Baker et al. 2004; Lewis et al. 2009; Luyssaert et al. 2008; Qie et al. 2017) concludes these forests continue to be a carbon sink even into very old age, making their conservation even more important for the climate.

3. Including 20 different pathways for improved stewardship of forests, croplands, grasslands, and wetlands.

4. In BECCS, solar energy and CO_2 are captured by plants through photosynthesis, with the energy converted into electricity or liquid fuels that can substitute for fossil fuels (together, bioenergy), while the CO_2 is injected underground to keep it out of the atmosphere (CCS).

5. Scientists make a distinction between *biogeophysical processes*, which influence climate through exchanges of momentum, heat, and moisture between land and atmosphere such as radiation reflected off of surfaces and exchanges of heat through evaporation of water, versus *biogeochemical processes*, which involve the cycling of elements between land and atmosphere, such as the carbon cycle, and affect climate through the concentration of greenhouse gases and radiatively active aerosols (nongas particles). This brief organizes the various processes through which forests influence climate by scale, rather than by these scientific categories of land-atmosphere interactions (although Figure 2 shows both). This section covers processes that have a significant and well-understood global radiative forcing impact, while the next section reviews recent scientific work on the nonradiative forcing climate impacts of forest change that nonetheless have a large impact at local, regional, and even continental scales.

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We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.