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REPORT

Not Just Carbon

Capturing *All* the Benefits of Forests for Stabilizing the Climate from Local to Global Scales

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US ARMY

Foreword

Our forests have enormous untapped potential. Most policy attention to date has focused on the potential of forests to store and remove carbon. While forests can be key in delivering around one-third of the annual mitigation needed to keep warming below 1.5°C, cutting-edge research suggests that tropical forests can also provide up to 50 percent more global cooling beyond what is accounted for by carbon emissions and sequestrations alone. A shortsighted focus on carbon neglects the many other ways that forests stabilize the climate—both locally and globally.

Through interactions with the atmosphere beyond the global carbon cycle, deforestation in the tropics also disrupts rainfall patterns up to hundreds of kilometers away—across national boundaries. Loss of forest cover also leads directly to increases in local average and extreme temperatures, exposing people and crops to heat stress. Failing to recognize the non-carbon effects of forests can make us blind to the other risks deforestation poses to food and water security, public health, and even global climate justice, and lead us to miss critical opportunities to avoid and reduce these risks.

We cannot afford to ignore these risks any longer.

To anticipate, prevent, or respond to those impacts, this report summarizes the science on the biophysical effects of deforestation on climate stability and explores the policy implications of the resulting impacts at three scales: global climate policy, regional cooperation on precipitation management, and national policies related to agriculture and public health. For each of these policy arenas, there are promising entry points to address current gaps through innovations in policies and institutions.

If we continue to focus exclusively on carbon, we will misallocate climate finance for both mitigation and adaptation and impose disproportionate burdens on the countries and communities least able to bear them. Further, we will miss opportunities to expand the forest protection agenda to include stakeholders promoting objectives such as agricultural productivity, water security, worker safety, and resilience to a changing climate.

Change starts with raising awareness among policymakers of the significance of these non-carbon effects for sustainable development objectives. Current institutional mandates may need to be stretched to address the effects of deforestation on rainfall and temperature and thus impacts on agriculture, water, and human health. While more research is needed to fully assess the scope and economic costs of various non-carbon effects of deforestations, the direction and size of those impacts are sufficiently clear to merit urgent action now.

Over the last two decades, tropical forests have been continuing to disappear at a stubbornly consistent rate. The implications of the climate investments gap in protecting tropical forests are even greater than previously thought. The benefits of forests beyond carbon gives governments, companies, and civil society even more reason to double down on global commitments to end deforestation.

ANI DASGUPTA
President & CEO

Executive Summary

THE CONTEXT

For at least the last 15 years, climate policymakers have increasingly recognized the importance of forests to meeting global climate goals. Since the initiation of negotiations at the United Nations Climate Change Conference in Bali in 2007 on a framework for what would become known as Reducing Emissions from Deforestation and forest Degradation (REDD+), strategies to mitigate global warming have included the protection and restoration of forests, especially those in the tropics.

HIGHLIGHTS

- Forests have significant—and overwhelmingly positive—effects on climate stability through biophysical processes that affect transfers of energy and moisture in the atmosphere, contributing to food and water security, protecting human health, and enhancing our ability to adapt to a warming planet.
- Accounting for these processes can significantly affect estimates of the impacts of deforestation on the global climate based on their interaction with the carbon cycle alone, rendering the global cooling effect of avoiding tropical deforestation as much as 50 percent greater.
- Removal of forest cover, especially in the tropics, increases local temperatures and disrupts rainfall patterns in ways that compound the local effects of global climate change, threatening severe consequences for human health and agricultural productivity.
- By failing to take these biophysical effects into account, current policies systematically undervalue forests' climate services, fail to anticipate the full range of climate risks associated with deforestation, and result in inequitable allocation of responsibilities and resources within and between nations.
- Policymakers should urgently recognize and address the full range of forests' climate regulation services through institutions operating at relevant scales, including the United Nations Framework Convention on Climate Change (UNFCCC), institutions for regional cooperation, and domestic agencies charged with promoting agricultural productivity and protecting public health.

Forests are also included in discussions of adaptation, mainly for their potential to buffer the local effects of extreme weather events, which are expected to become more frequent and severe due to global warming: forested watersheds offer protection from landslides and flooding following heavy rainfall, while mangrove forests attenuate wave damage during coastal storms and sea-level rise. Forest biodiversity is also increasingly recognized as a factor that enhances forest-reliant peoples' resilience to climate change. The package of forest-related commitments announced at the global climate summit in Glasgow in 2021 put forests high on the global agenda.

Consistent with the framing of the United Nations Framework Convention on Climate Change (UNFCCC), which focuses on limiting greenhouse gas (GHG) concentrations in the atmosphere, attention to forests in climate policy has largely focused on the role of forests in the global carbon cycle. Indeed, forests are globally significant as a *source* of CO_2 emissions, constitute the largest terrestrial carbon *sink*, and provide a natural technology for carbon dioxide removal (CDR). Scenarios published by the Intergovernmental Panel on Climate Change (IPCC) make clear that reaching the goals of the Paris Agreement will require ending deforestation; maintaining carbon-dense, intact forests; and dramatically scaling up forest restoration to achieve a balance between *anthropogenic* GHG emissions and removals by midcentury (IPCC 2019b).

Science examining the ways forests interact with the atmosphere other than via GHGs continues to illuminate the significance of various biophysical and biogeochemical pathways through which forests stabilize the climate (see, e.g., Ellison et al. 2017 and Lawrence et al. 2022). These pathways include forests' effects on how much of the sun's energy is reflected back into space (both directly by absorbing energy, and indirectly by generating reflective cloud cover); how forests cool the earth's surface and near-surface air through *evapotranspiration* (the movement of water from land into the atmosphere by *evaporation* from surfaces and *transpiration* from plants); how forests generate and transport atmospheric moisture through such evapotranspiration in ways that affect downwind precipitation patterns; how the roughness of forest canopies affects wind and atmospheric mixing, and thus the distribution of heat and moisture in the atmosphere and downwind climates and rainfall; and how the organic compounds and small particles generated by forests affect atmospheric chemistry and cloud formation. These effects vary in intensity across latitudes and scales, depend on the *background climate,* and interact with each other in complex ways, not all of which are understood in depth. Nevertheless, the overall picture is clear: recent quantification of the net effects of forest cover loss on *radiative forcing* and energy transfer through these pathways makes it imperative that they be integrated into mitigation and adaptation policies and strategies, rather than simply considered as "cobenefits," to realize the full climate benefits of forests.

Forests are integral to the functioning of the entire global climate *system* and should not be understood as simply mechanical devices that store and release carbon. The effects of GHG emissions or removals from forest cover change may be significantly dampened or amplified by the additional pathways through which forests affect the climate, both globally and locally. These additional interactions between forests and the climate challenge the conventional wisdom that "a ton is a ton is a ton" when it comes to climate actions to slow GHG emissions or remove carbon dioxide (CO_2) from the atmosphere. We must improve our understanding of the scale and direction of forests' non-carbon climate regulation services, and design policies that seek to maintain these services whether the forests themselves are nearby or on the other side of the planet.

Accounting for the non-GHG effects of keeping tropical forests standing increases estimates of their potential contribution to global cooling by 50 percent, in addition to moderating rainfall disruptions and extreme temperatures in ways that are essential to local adaptation and resilience (Lawrence et al. 2022). Healthy forests regulate local climate, and forest loss will amplify climate risks, increase extremes, and lead to a potential breakdown of forests' local and global climate regulation services. These findings add particular urgency to the need to protect tropical forests before deforestation robs the world of these essential services. By failing to take the broader climate benefits of forests into account, climate policies will systematically undervalue forests' climate services, fail to anticipate the full range of climate risks associated with deforestation, and result in inequitable responses to those climate risks and responsibilities within and between nations.

As the world seeks solutions to the climate crisis, forests are among our biggest allies. The science is sufficiently clear regarding the scale and direction of forests' climate regulation services through biophysical processes to inform the design of policies to maintain those services. Climate policies must capture all the benefits of forests for stabilizing the climate and adapting to climate change.

ABOUT THIS REPORT

This report has several objectives.

First, the report aims to make the scientific literature about the full range of effects of forests on the climate accessible to policymakers and other stakeholders. The analysis in this report constitutes part of, and builds on, a broader set of analyses funded by the Climate and Land Use Alliance. Other analyses include a scientific synthesis of prior research into the biophysical effects of forests on the climate prepared by a team led by Deborah Lawrence of the University of Virginia (Lawrence et al. 2022), amodeling study of the effects of deforestation in the Amazon on increased temperature and human exposure to heat stress (Alves de Oliveira et al. 2021), and analyses of the economic impacts of deforestation on regional agriculture through biophysical effects (Leite-Filho et al. 2021; Flach et al. 2021).

Second, the report seeks to highlight for policymakers and other stakeholders the policy implications of forest-climate interactions beyond GHGs. It identifies a few of the most significant risks to climate stability at global, regional, and national and local scales posed by the loss of forests and their biophysical interactions with the atmosphere, with a focus on the tropics. It then assesses illustrative gaps in current policies and institutions needed for managing those risks.

Third, the report suggests promising directions for future research, policy development, and institutional innovation to close identified gaps. In so doing, the analysis draws on relevant policy analogues presented by experience in addressing other governance challenges related to forests, water, or the atmosphere, and interactions among them.

WHAT IS THE SIGNIFICANCE OF THE ADDITIONAL IMPACTS ON CLIMATE STABILITY CAUSED BY FOREST LOSS?

The policy implications of this deeper understanding of forest-climate interactions are clear and profound. While some specific aspects of the science behind biophysical processes remain uncertain, the overall implications of the science are clear—the magnitude, direction, and geographic gradients of many of the biophysical effects of forest cover change are now sufficiently established to merit an urgent policy response. Estimates of the value of tropical forest conservation for global cooling would need to be adjusted up to 50 percent higher than the value of such conservation via the carbon cycle alone—roughly equivalent to counterbalancing the recent annual human-caused emissions from all sources from Russia. The local impacts of deforestation—such as a 4.5°C (Celsius) increase in average daily high temperatures from nearby forest loss in the tropics—are already subjecting people and crops to heat stress. The significant yet overlooked cooling services of forests through biophysical processes need to be recognized in land use and climate finance decision-making (Lawrence et al. 2022).

Failure to take the biophysical effects of forests on climate into account in policy risks misallocating investment across various mitigation and adaptation options based on an incomplete understanding of their value to climate stabilization and resilience. Quantifying and properly valuing *all* the effects of forests on climate stability would illuminate that the gap between the current share of climate finance allocated to forests compared to their mitigation and adaptation potential is even larger than previously thought.

Ignoring the biophysical impacts of forests in relevant policy arenas is likely to result in inequitable outcomes within and between countries. For example, failure to adjust national climate accounting based on GHGs alone results in overstating the global cooling effects of forests located in countries at higher latitudes and understating their importance in tropical countries. Global averages mask significant differences in the local impacts of deforestation, and the increases in temperature extremes and changes in rainfall due to deforestation are having an outsized impact on those people least responsible for the changes and least equipped to adapt. Within countries, for example, the increased risk of heat stress due to deforestation is likely to be imposed most keenly on rural farmers and agricultural workers, while Indigenous and local communities that depend directly on forest ecosystems are most vulnerable to disruption of the services provided by those ecosystems.

SELECTED POLICY IMPLICATIONS

To respond to the many biophysical effects of forests, governance of climate stability must include policy arenas and institutions operating at regional, national, and local scales and across sectors, in addition to those focused on global climate policy. Implicitly equating "climate change" with "global warming"—and focusing only on carbon and its impact on global radiative forcing—narrows the relevance of forest cover loss in ways that exclude significant and immediate impacts of deforestation on the local climate as it is experienced by people on the ground. Some of these impacts are of larger magnitude and thus of more immediate relevance to lives and livelihoods than the impacts of global processes. Focusing only on the global impacts of deforestation also leads to incomplete responses by subglobal policies and institutions. Responses that include the additional biophysical impacts on climate stability require breaking down the silos that separate policy agendas related to agricultural production, water resources management, and public health from those that focus on forests. For example, local adaptation planning needs to take into account the compounding effect of local deforestation on local temperature extremes in addition to the increases expected from global warming.

The biophysical effects of forests on the climate vary by scale, so their policy implications may vary as well, although the cumulative effects all point toward the need for policies to consider the broad range of benefits provided by forests. Some of these effects result in global cooling or warming—amplifying or dampening the greenhouse effect of forests through carbon exchanges with the atmosphere—and thus require integration into global climate governance. Other effects are transported by the atmosphere across distances ranging up to continental scale, suggesting the need for transboundary institutional frameworks. Yet other effects are primarily local, impacting the climate experienced by agricultural crops and human communities affected by maintaining nearby forest cover or its removal, implicating local land-use decision-making and adaptation planning.

At the global scale

The biophysical impacts of forests on climate are sufficiently significant to merit a place on global mitigation and adaptation agendas, above and beyond the importance of forests to GHG fluxes. Conservation of tropical forests is even more important for mitigation and adaptation than previously thought, providing enhanced global cooling, maintaining rainfall patterns at continental scales, and protecting local people and their crops and livestock from extreme temperatures.

Despite its focus on reducing the concentration of GHG emissions in the atmosphere, the UNFCCC could accommodate some of the implications of forest-climate interactions beyond GHGs. The framing of the Paris Agreement in terms of temperature goals provides an opening to address the biophysical roles of forests in global cooling, and there is nothing in the Convention preventing policymakers from doing so immediately. The Warsaw Framework for Reducing Emissions from Deforestation and forest Degradation (REDD+) provides opportunities to do so, for example, by its encouragement of capturing and reporting on cobenefits. The first Global Stocktake under the Paris Agreement provides an opportunity to introduce the additional climate benefits provided by forests for both mitigation and adaptation into the UNFCCC science and policy processes.

At the regional scale

Deforestation of large areas could disrupt historical rainfall patterns within and across national boundaries, posing significant risks to future water and food security. For example, the moisture generated by the forests of the Brazilian Amazon has been shown to decrease the severity of droughts within Brazil and is estimated to contribute between 13 and 32 percent of annual precipitation in the downwind countries of Argentina, Bolivia, Paraguay, and Uruguay (Keys et al. 2017). Moisture generated by the Congo Basin's forests is estimated to contribute about half of the precipitation in the city of Kinshasa's watershed (Keys et al. 2018).

While no institutions currently address the atmospheric moisture flows generated by forests, existing agreements for governing transboundary surface water and air resources provide some lessons and models. For example, the Convention on Long-Range Transboundary Air Pollution has succeeded in reducing the pollution that causes acid rain, in part by strengthening the science on its causes, pathways, and impacts on ecosystems. Regional agreements and bodies designed to manage transboundary river basins could be expanded in membership and mandate to address atmospheric moisture flows, although they also illustrate the challenges of such cooperation.

At the national and local scales

Deforestation in the tropics is already leading to increased average and extreme local temperatures on par with, and compounding, increases expected from global warming, threatening agricultural productivity and human health. The effects of nearby deforestation on reducing the productivity of soy in the Brazilian Amazon and *Cerrado* are now well documented (Flach et al. 2021). Studies conducted in Indonesian Borneo have documented a shortening of safe working hours, lower productivity, and cognitive impairment of agricultural workers due to deforestation-induced heat stress, while modeling links temperature increases associated with deforestation to increased mortality from all causes. Studies project that continued large-scale deforestation in the Brazilian Amazon, combined with climate change, could expose 12 million people to potentially lethal extreme heat stress by 2100 (Wolff et al. 2021; Alves de Oliveira et al. 2021). In both cases, modeled scenarios of continued deforestation show these impacts would increase significantly (Flach et al. 2021; Wolff et al. 2021; Alves de Oliveira et al. 2021).

National and local land-use decisions and adaptation planning need to take deforestation-induced temperature change into account. Raising awareness of the effects of deforestation on agricultural productivity could change the politics of land-use decision-making, as agricultural ministries, lobbies, companies, and farmers realize that they are the beneficiaries of forest protection. Public health officials and agencies charged with regulating worker safety could be constituencies for forest protection if made aware of the implications of deforestation for their objectives.

Understanding the loss of forest services as a local threat to human health and local economies is more likely to gain political traction than appealing to the global values of forests for climate change mitigation or biological diversity conservation. Because nearby forest cover change has more immediate local effects and is more amenable to local control compared to either the local effects of global climate change or the global climate effects of nearby forest cover change, public sector, private sector, and civil society leaders are more likely to be motivated and empowered to take action to address it.

WHAT'S NEXT?

In addition to taking steps toward addressing the scale-specific policy and institutional gaps highlighted above, concerted action by scientists, advocates, and policymakers on communications, research, and research-policy linkages could help to accelerate society's response to the additional impacts of forests on climate stability beyond the carbon cycle.

A first step is to raise awareness of *all* the benefits of forests for stabilizing the climate, emphasizing the overlooked science of the biophysical effects of forests on climate stability and its many policy implications. The full range and significance of forests' impacts on climate stability is unfamiliar to most forest experts, much less nonexpert climate policymakers and actors in other policy arenas. Communicating this knowledge in ways that are accessible to those who need to act on it—and to those who will be most affected by the failure to act on it—is thus a priority for scientists and policy advocates working at the forests-climate interface.

A second step is to get the biophysical effects of forests on the climate and associated impacts on agriculture and human health placed on the agendas of relevant policy arenas and institutions. Such placement will require champions to advocate for the appropriate prioritization and economic valuation of forests' biophysical services across various agreements, laws, and regulations, as well as integrated into private sector decision-making related to investment and climate risk management.

Individual countries could accelerate needed action by investing in further research and analysis to quantify the biophysical effects of forests on climate, and include these estimates in their Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs), REDD+ plans, or even national inventories. Such leadership would stimulate a reckoning with methodological issues, such as how to quantify the biophysical effects of forest cover change in terms of global warming potential or CO_2 equivalents, as well as with the financial and political implications of adjusting accounting systems previously limited to GHGs.

In parallel, public and private financiers could invest in further research and spatial analysis to estimate the economic and financial impacts of forest cover change mediated through the atmosphere. Policymakers and private sector investors alike need to know the full costs of decisions to clear forests—as well as who is likely to bear those costs. Only then can those costs be compared to any benefits of deforestation and/or the costs of adaptation to the resulting climate instability predicted to result from forest loss.

To advance the above objectives, forums are needed to bring together researchers and policymakers to ensure that policy is informed by research, and that research is directed to the most policy-relevant issues.

CHAPTER 1

Introduction

The sun rises quickly over the summer soy crop in the Brazilian State of Pará. By 7 o'clock in the morning, the temperature is already 36°C (Celsius). This area—and tens of kilometers in every direction—was once covered by lush tropical rainforest, which kept the temperature on the ground below 33°C, even at midday. Now, the daylight hours when it is possible for laborers to work outside without suffering from heat stress have shrunk by over an hour a day.

Crops are also affected by the widening extremes of temperature. Yields of soybean fields adjacent to forests decrease by 10 percent or more when those forests are cleared. Yet the implications of deforestation for the health of rural laborers or for agricultural productivity are not taken into account in federal or state land-use policies.

By precipitating rain from the moist air blowing in from the Atlantic, and recycling that moisture to areas further inland, the forest maintained a wet climate not only locally, but hundreds to thousands of kilometers (km) downwind. Now, it's hotter, and winds unimpeded by trees are drying the soil rather than bringing rain. To the south in Argentina, farmers have suffered debilitating drought plausibly linked to deforestation in the Amazon. The 2017–18 drought caused $3.4 billion in losses in grain exports alone. Yet no forum exists for Argentinian officials to represent their interests in the impacts of land-use change outside the country's borders on rainfall within.

The warmer, drier conditions render the land more vulnerable to fire, which prevents the forest from full recovery even on abandoned land. Forest degradation penetrates the edges of intact forests and fuels a vicious and expanding cycle of forest loss, heat, drought, fire, and more forest loss, exacerbated by warming of the global climate. Scientists warn that for the Amazon Basin, a tipping point is near, which could flip the entire ecosystem from rainforest to savanna grassland. The accompanying release of carbon from forests into the atmosphere would doom the planet to worst-case-scenario warming.

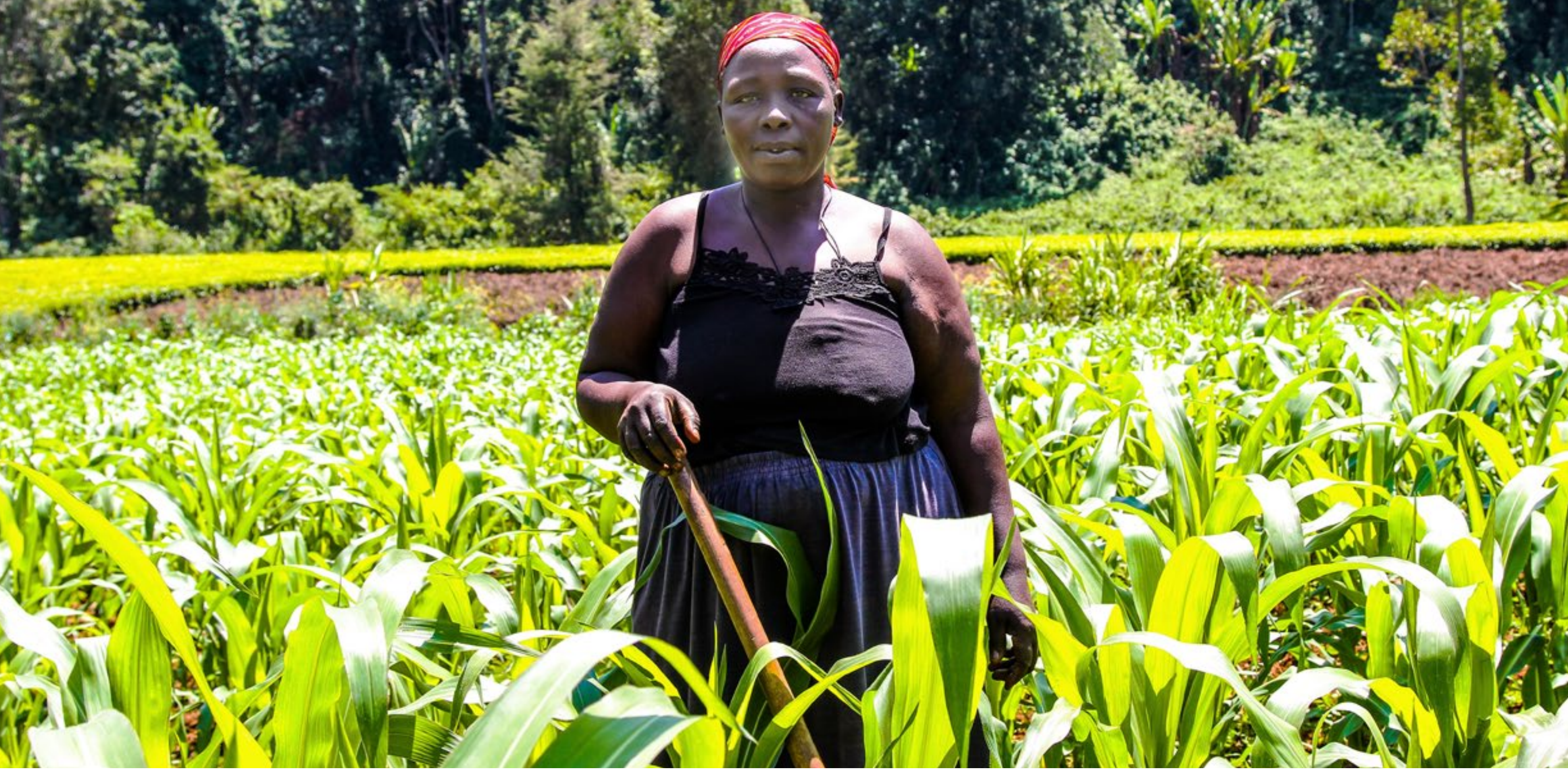
The stylized description of the impacts of deforestation on climate in this and the following paragraphs is based on Flach et al. 2021; Leite-Filho et al. 2021; and Lovejoy and Nobre 2019

Even absent the risk of crossing a tipping point, protecting and restoring the forests in the Amazon Basin and elsewhere in the tropics would have an outsized impact on global climate stability. Not only do growing trees pull significant amounts of carbon out of the atmosphere, but by encouraging cloud formation through their moisture releases and *surface roughness*, they ensure that more energy from sunlight is reflected back into space. These biophysical effects, which vary in intensity by latitude, are not included in the accounting used by the UNFCCC, which focuses only on GHGs. The resulting implicit bias against protecting and restoring tropical forests to capture their full global climate cooling potential compounds the relative neglect of this most effective "natural climate solution" when priorities for climate finance are being set.

Forests moderate local temperatures; affect patterns of rain, wind, and cloud formation; and thus influence both how much energy stays within the earth's atmosphere, and how that energy is distributed vertically in the atmosphere and within and between continents. Forest ecosystems are critical components of the earth's climate *system*, and not just machines that mechanically absorb or release carbon. When forests are cleared, those functions are disrupted in ways that can have more significant impacts in particular places than the local effects of global temperature rise caused by the accumulation of GHGs in the atmosphere. The ways that forests affect climate stability other than through GHG emissions and removals constitute a significant, neglected dimension of climate change mitigation and adaptation options.

THE PURPOSE, AUDIENCE, AND STRUCTURE OF THIS REPORT

The purpose of this report is to further inject the growing scientific understanding of these additional, largely biophysical effects of forests on climate change into climate, forest, and water policy contexts where they have, to date, been too frequently missing or unaddressed. For the purposes of this report, we will use the term biophysical as shorthand to refer to the multiple ways that forests affect climate stability other than via GHG emissions and removals. As some of the effects of forests on atmospheric chemistry (i.e., through the release of primary biological aerosol particles [PBAPs] and biogenic volatile organic compounds [BVOCs]) are



not biophysical, nor operate primarily or solely through the greenhouse effect, we will be explicit regarding the inclusion or exclusion of those "biogeochemical" effects when the distinction is material to the analysis. We pursue this objective in two ways: first, by presenting the science in a way that is accessible to nonscientist policymakers; and second, by identifying gaps in selected policy frameworks that govern forests' impacts on the atmosphere and hence climate stability.

This report provides a comprehensive framework for considering the policy implications of *all* the interactions between forests and the atmosphere that affect climate stability. It highlights how considering forests' biophysical effects on temperature and rainfall requires adjusting and expanding beyond a narrow focus on the impacts of forest cover change on the global climate through GHG emissions and removals. While previous analyses have called attention to these issues (see, e.g., Ellison et al. 2017), the gap between science and policy remains large.

We hope that our summary of the science and illustrative examples of its policy implications will provide readers with both the tools and the motivation to engage in a broader identification of current policy incoherence and gaps. Further, by identifying possible entry points in existing policy frameworks, we aspire to prompt discussions regarding what to do about those gaps that will ultimately lead to policy improvements and better forest-climate outcomes.

Who Should Read This Report?

Our target audiences include at least three types of policymakers, and those who seek to influence them.

First are those involved in forest policy arenas across scales. While many policymakers are aware that forest cover provides local cooling services, many may not yet be aware of their relative magnitude or the timescale on which the loss of those services is being experienced compared to the GHG-induced warming. Understanding the additional benefits of maintaining forests for climate stability will help them be better advocates for forest protection. For example, when Ministries of Agriculture or Trade argue in favor of forest conversion, ostensibly to increase food security or agricultural exports, Ministries of Forestry or Environment will be equipped to explain how such policies could be self-defeating.

A second target audience comprises those involved in climate policy arenas at national and international levels. To meet global climate mitigation targets in the most effective and efficient ways possible, they need to understand how forests' biophysical impacts on global temperatures can either amplify or dampen the impacts of GHGs. Further, understanding the local impacts of forest cover change on climate stability will enable them to more accurately forecast adaptation finance needs, and target resources to areas where mitigation and adaptation synergies can best be captured.

The third audience for the report comprises those involved in sectoral policy arenas such as water, agriculture, and health, including staff of multilateral development banks and specialized technical agencies; regional bodies charged with governing transboundary natural resources; and, in particular, relevant government officials at national levels and below. Raising their awareness of how forest cover change affects their interests could help them recognize their stakeholdership in land-use decision-making and activate them as constituencies for forest protection. That same awareness could help them understand and prepare for the relative size and timing of adaptation challenges when the more immediate and variable local impacts of forest cover change on climate stability are added to those of global warming.

Other audiences will also find our analysis relevant to their concerns, including private sector companies and financiers whose commercial interests may be materially affected by the additional impacts on climate stability caused by forest change. Civil society organizations that seek to influence the behaviors of public and private actors that affect forests and climate change will find additional evidence and arguments to support their advocacy efforts on behalf of the world's forests and forest peoples.

Roadmap to the Report

This report is organized as follows:

The remainder of Chapter 1 provides background to place this analysis in the broader context of the interactions between forests and climate via the global carbon cycle, and to offer reasons why non-carbon pathways have been relatively neglected by policymakers. It then presents a framework for analyzing policy gaps related to biophysical processes that will be utilized in subsequent chapters.

Chapter 2 presents a summary of the science linking forests and climate stability through both GHG and non-GHG pathways, with an emphasis on the latter, for readers interested in understanding that science in greater depth. Drawing largely on recent contributions to the peer-reviewed literature, the chapter translates findings that are largely inaccessible to the nonexpert into more familiar language, accessible diagrams, and intuitive examples. As Chapters 3, 4, and 5 each begin with a brief summary of the science relevant to that chapter, readers interested in getting straight to the policy implications can skip Chapter 2. Similarly, text boxes throughout the report provide optional detours for readers interested in greater depth on specific examples or policy analogues and can be skipped by others.

Chapter 3 considers policy gaps and opportunities for addressing the effects of forest-atmosphere interactions at the global level. The chapter focuses on the biophysical pathways through which forests affect global average temperature changes and more local climate effects relevant to global policy, and on the United Nations Framework Convention on Climate Change (UNFCCC) as the most relevant policy arena.

Chapter 4 analyzes gaps and opportunities in policies and institutions necessary to address the biophysical roles of forests in stabilizing the climate at the regional scale. The chapter focuses on the role of forests in *terrestrial moisture recycling (TMR)* and associated *precipitationsheds*, especially those that span national boundaries such as the

Amazon and Congo Basins. It examines experience with institutions created to manage other transboundary natural resource management challenges such as air pollution and international rivers.

Chapter 5 describes the implications of forest cover loss in destabilizing the climate at local scales, and the effects of extreme temperatures on human health and agricultural productivity. With a focus on examples from Indonesian Borneo and the Brazilian Cerrado, the chapter suggests how failure to consider these implications in land sector decision-making will likely present costly adaptation challenges for the health and agricultural sectors.

Chapter 6 summarizes key takeaway messages from preceding chapters. It also briefly identifies other implications of the improved scientific understanding of biophysical pathways not already included in previous chapters, such as priorities for further research, and the need for financial disclosure of risks due to deforestation-related climate instability.

To render the report more readable and accessible, the executive summary, introduction, and conclusion, and the stylized stories that begin each of the first five chapters, avoid extensive scientific references. However, Chapter 2 and the science summaries that begin Chapters 3, 4, and 5 are more systematically and comprehensively referenced. Throughout the report, terms that are defined in the glossary are in italics at first use.

BACKGROUND

Didn't We Already Know Forests Are Important to Climate Change?

To date, the science linking forests to climate change that is most familiar to policymakers focuses on the role of forests in the global carbon cycle. While some trees and forests emit methane (Covey and Megonigal 2019)—another greenhouse gas—by far the most significant impact of forests on the global climate is through absorbing carbon dioxide during photosynthesis, storing carbon in trees and soils, and releasing that carbon to the atmosphere as carbon dioxide when forests burn or deadwood decomposes. Every scenario for avoiding catastrophic climate change requires that current rates of deforestation be halted and reversed, with land sector removals balancing residual fossil fuel emissions as decarbonization of the global economy proceeds toward net-zero by 2050 (IPCC 2019b).

The importance of this carbon emissions mitigation function is well recognized in global climate policy. Under the UNFCCC, all countries are required to account for land sector emissions and removals as part of their reporting obligations. Emissions from the forest sector are especially significant for many developing countries in the tropics, where deforestation can be the largest source of national emissions, and thus a key target for reductions. Conversely, several industrialized countries such as Canada, Russia, the United States, and many European countries have in the past and are likely in the future to rely on carbon sequestration by temperate and boreal forests to help them meet their climate goals, accounting for them in ways that provide a ton-for-ton counterbalance against at least some of their fossil fuel emissions.

The forest sector is the only one singled out for special attention in the 2015 Paris Agreement. Article 5 of that agreement incorporates by reference a negotiated framework of "policy approaches and positive incentives for activities relating to reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries" known as REDD+. Of significance to the focus of this report, Article 5 also mentions "the importance of incentivizing, as appropriate, non-carbon benefits associated with such approaches" (UNFCCC 2015).

> The forest sector is the only one singled out for special attention in the 2015 Paris Agreement.

The idea that became REDD+ entered international climate negotiations under the UNFCCC in 2007 amidst high expectations. Demand from industrialized countries for low-cost emission reductions was expected to create a compelling value proposition for decision-makers in developing countries to protect forests, and new satellite-based monitoring technologies would ensure that claimed emission reductions were real (Seymour and Busch 2016). Over the course of the next decade, dozens of countries supported by international donors invested in creating the institutional infrastructure necessary for REDD+ implementation, including national forest monitoring systems, strategies, and safeguard systems (Duchelle et al. 2019).

International and national REDD+ processes have also stimulated increased attention to the rights and roles of Indigenous peoples as stewards of much of the world's remaining forests (Seymour and Busch 2016). As rights-holders, custodians of traditional knowledge, and frontline forest managers, Indigenous and other forest communities are increasingly recognized as essential partners in forest protection and entitled to an equitable share of benefits from forest-related climate finance.

For the most part, however, the prospect of significant and certain payment for performance in reducing forest-based emissions through REDD+ mechanisms failed to materialize, with the result that forests and other "natural climate solutions" in the land sector continued to receive less than 3 percent of climate mitigation finance (Forest Declaration Platform 2021). This amount is an order of magnitude less than their potential to avoid and sequester GHG emissions, with estimates of their cost-effective mitigation potential of more than 30 percent of reductions needed by 2030 (Griscom et al. 2017). It remains to be seen whether the package of forest-related financial commitments made at the UNFCCC conference in Glasgow in 2021 will materially close that gap.

Lack of financial incentives may be one reason why many national mitigation strategies of developing countries do not yet reflect forests' potential to reduce or remove GHG emissions. Although three-quarters of countries included forests as part of their overall commitment in the first round of submissions of Nationally Determined Contributions to the goals of the Paris Agreement, most did not specify quantitative targets for the sector (Bakhtary et al. 2020). There is significant headroom within existing climate policy frameworks to strengthen attention to forests as a strategy for both climate mitigation and adaptation (Sato and Nakamura 2019).

And yet, the full gap between the potential of forests to contribute to climate mitigation and adaptation and the share of climate-related political attention and finance focused on tropical forests is even greater if biophysical processes through which forests affect climate stability are taken into account. In light of the significant policy attention that has already been dedicated to the role of forests in the global carbon cycle, this report focuses primarily on presenting the science and exploring the policy implications of those biophysical pathways, including *albedo*, moisture recycling, and surface roughness. (The report also briefly describes and notes the complexities introduced by aerosols and non-GHGs emitted into the atmosphere by forests, ranging from pollen to *terpenes*, which are neither GHGs

nor biophysical processes.) However, the GHG mitigation potential of forests provides an important benchmark against which to assess the relative significance of pathways other than via their role in the carbon cycle. Further, current climate policy frameworks that *do* focus primarily on carbon, including REDD+, offer important—although not exclusive—entry points for imagining how those biophysical pathways might be recognized and valued in relevant policy arenas.

How Are Biophysical, Aerosol, and Non-Greenhouse Gas Pathways Different from GHG Pathways?

Compared to the role of forests in the global carbon cycle, the science linking forests to climate stability through biophysical, aerosol, and non-GHG pathways is complex, and the policy implications can be quite different than those for GHG emissions and removals. GHG and non-GHG pathways differ in at least five important respects.

First is the level of complexity. In contrast to the relative simplicity of forests' roles in sequestering, storing, or releasing carbon that reduces or contributes to the accumulation of CO_2 in the atmosphere; biophysical, aerosol, and non-GHG pathways are collectively more complex. As it is, the ability of a single area of forest to simultaneously release and sequester carbon renders measurement and accounting for land sector emissions more challenging than measurement and accounting for fossil fuel emissions. But these other pathways include multiple types of forest-atmosphere interactions that don't necessarily pull in the same direction as GHG pathways or with each other, and indeed may interact with each other and with other processes in nonlinear ways. For example, deforestation in boreal zones results in albedo-related cooling, which has been hypothesized to also cool polar oceans, inducing greater sea ice—which would in turn increase albedo, amplifying the cooling effect.

Second is location dependence. Unlike the effect of forests on climate change through the global carbon cycle—in which the impact is indifferent to where on the planet a particular ton of carbon is emitted or absorbed ("a ton is a ton is a ton")—the impacts of several biophysical, aerosol, and non-GHG pathways do depend on where they take place. The biophysical and aerosol effects of forest cover on the atmosphere can depend significantly on both latitude and background climate, and even background atmospheric chemistry. For example, the albedo effect dampens the climate-cooling impact of forest carbon storage in higher latitudes, while amplifying it in the tropics. The cooling effect of forests through *evapotranspiration* is more pronounced in wetter climates. And the biogenic volatile organic compound (BVOC)-induced production of *ozone* mentioned above depends on the atmospheric presence of nitrogen oxides.

Third is spatial pattern. The spatial pattern of forest cover change matters for biophysical pathways. A given amount of carbon emitted from the clearance of 100 widely scattered small patches of forest would have the same climate effect through the GHG pathway as an equivalent amount of carbon from a single patch 100 times as large; however, that would not be the case for the warming and drying effects mediated through evapotranspiration or wind.

Fourth is distance dependence. While the greenhouse effect of forests through the global carbon cycle—and the incremental effect of a particular change in forest cover on the global climate—is distributed across the globe through atmospheric mixing, the biophysical, aerosol, and non-GHG effects and their manifestations reverberate through different scales from global to local. They are often experienced more locally through increased climatic variation and large local changes in average temperature and rainfall. While deforestation in one locality would have a trivial impact on the average global or local temperature via the GHG effect alone, it could have a major impact on the heat extremes experienced in that locality. Further, the magnitude of some of the effects are dependent on distance and even direction from the location of forest cover change. For example, a city would be vulnerable to decreases in rainfall if deforestation took place in its upwind *precipitationshed.*

Finally, there is temporal dependence. There can be a divergence in the temporal dimension of GHG and non-GHG impacts on climate. While GHG emissions affect the climate through gradual warming over the residence time of accumulating GHG molecules in the atmosphere, the local effects of several biophysical impacts of forest cover change on the climate are experienced immediately. Indeed, many people are already living in climates that are 2 or more degrees Celsius warmer than before local deforestation took place. Biophysical, aerosol, and non-GHG impacts of forest cover may also vary by season: forests in the midlatitudes have a mild cooling effect in the summer months through evapotranspiration, and a mild warming effect in the winter due to the albedo effect (Lawrence et al. 2022).

> Despite the greater complexity compared to GHG pathways, the biophysical effects of forests on the climate are sufficiently well-understood that the impacts of forest cover change through those effects must be addressed.

Although the effects of forest cover change on climate stability via biophysical pathways are still subject to active research to fill in missing pieces, in many cases their direction and relative magnitude are sufficiently clear to be incorporated into current decision-making. For example, although it is clear that large-scale land-use change can affect climate in remote locations through changes in atmospheric circulation patterns, models do not always agree on the direction or magnitude of such impacts. By contrast, the effects of land cover change on albedo and local temperature are well understood.

Thus, despite the greater complexity compared to GHG pathways, the biophysical effects of forests on the climate are sufficiently well understood that the impacts of forest cover change through those effects must be addressed in climate and other policy arenas.

Why Have Biophysical Pathways Been Neglected in Climate Policy?

Even though there is mounting evidence that the biophysical impacts of deforestation are already affecting the global climate, as well as human health, agricultural productivity, and other Sustainable Development Goals (SDGs) across scales, these impacts of forests on climate stability are not adequately captured in relevant policies, institutions, and climate change accounting practices. There are two main reasons for these gaps.

The first relates to the scale of climate policy attention to date. "Climate change" is popularly equated with "global warming," and so it follows that far more attention has been paid to forest-related changes in climate that are experienced at the global scale—primarily the carbon impacts—than to changes in local and regional climates as a result of deforestation. Some people might think of local temperature or rainfall as "weather"—and it can be—but climate is simply the longer-term patterns (averages, extremes, and variability) of weather. And forest cover changes can cause very large and persistent directional changes in local and regional temperatures and rainfall. The local impacts of forest cover change on such long-term patterns, in fact, also constitute "climate change" but are not often recognized as such.

The second reason relates to the scope of climate policy attention. It follows that if climate change is understood first and foremost as a global phenomenon, relevant policies would be associated with the main instrument for global climate governance, the UNFCCC. The UNFCCC was established with a foundational purpose of controlling emissions of GHGs. Thus, while scientific bodies such as the Intergovernmental Panel on Climate Change (IPCC) have long included biophysical processes such as albedo in their assessments and quantification of global temperature patterns, equating "climate policy" with "global climate governance" has limited policymakers' attention to forests' roles in emitting or removing GHGs at the expense of other relevant functions—even those that have been well-understood for decades. As a result, forest-atmosphere interactions that are more local in scale, and operate through pathways other than GHGs, are implicitly ignored, or are at best relegated to the status of "GHG mitigation cobenefits" or as relevant primarily to adaptation rather than mitigation. This limitation may be shifting with the Paris Agreement's expression of goals in terms of temperature targets, but nevertheless has been baked into the UNFCCC's structure and instruments.

What Are the Risks of Such Neglect?

These gaps in policies, institutions, and accounting for forests' impacts on climate stability pose a risk that efforts to mitigate and adapt to climate change will be at best suboptimal, or at worst have perverse effects, such as in the following examples:

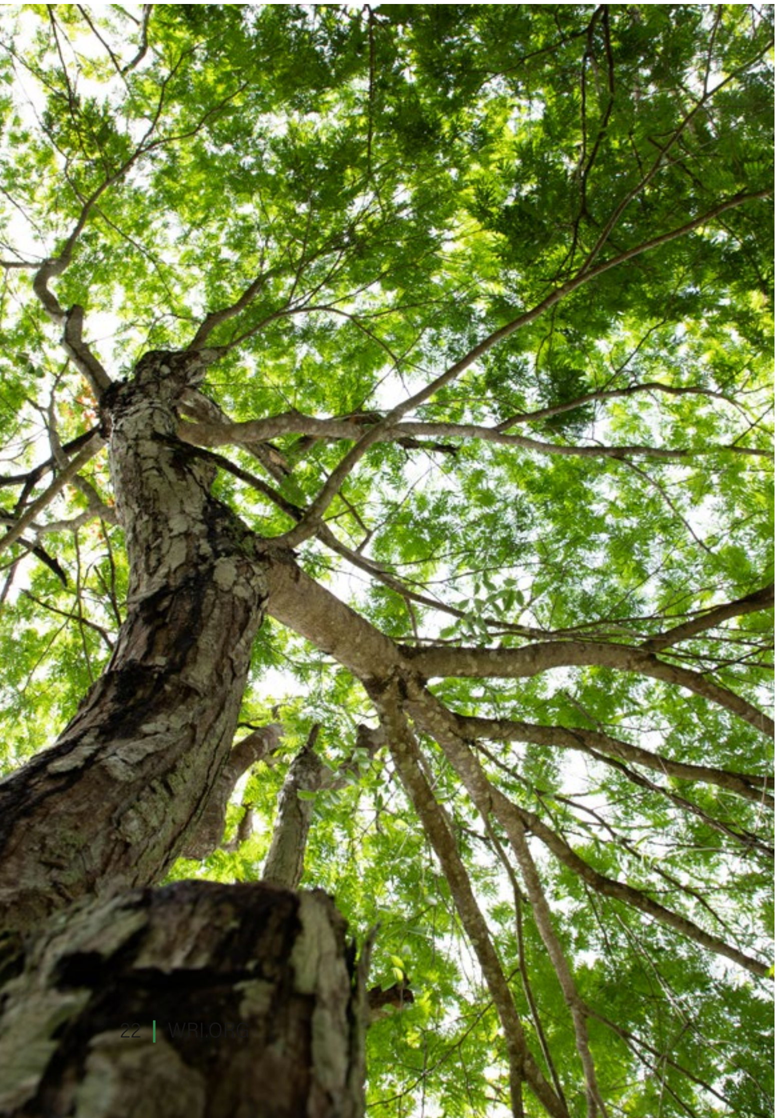
- At the global level, the effect of forest cover on how much of the sun's energy is reflected back into space varies by latitude. In the tropics, even though tree cover absorbs more sunlight than bare land, more forests can lead to cooling due to the reflectivity of cloud cover generated by evapotranspiration. In the boreal zones, by contrast, more forests lead to warming given the lower reflectivity of trees compared to snow. Not taking these differences into account in land sector mitigation priorities risks overinvestment in some activities and geographies, such as tree-planting in higher latitudes, and underinvestment in others, such as conserving tropical forests.
- At the regional level, large expanses of forest transport moisture across continents through evapotranspiration. Deforestation risks disrupting rainfall patterns and thus water resource availability in distant geographies. Not taking this forest-climate impact into account in land-use decision-making could inflict food insecurity on neighboring countries and precipitate international conflict, or even threaten the productivity of critical "breadbasket" regions and global food supplies.
- Locally, forests moderate temperature extremes, with important implications for human health and agricultural productivity. While policymakers have long recognized the *urban heat island effect* caused by the ability of buildings and pavement to absorb and store heat, few are aware of what might be called a "rural heat island effect," which occurs when the cooling functions of forests such as shade and evapotranspiration are removed. Consideration of the costs of adaptation to such extremes, if factored into decisions about whether to convert forests to other land uses, could change the outcomes of those decisions.

A cross-cutting risk of failing to conserve the additional climate benefits of forests is amplifying the adverse consequences for climate change for Indigenous Peoples and local communities. The direct dependence of such communities on forests for their livelihoods renders them especially vulnerable to disruptions in forest-based ecosystem services, whether directly due to deforestation and forest degradation or indirectly due to climate change (IPCC 2022).

An objective of this report is to raise awareness of such risks and suggest directions for policy and institutional innovation for addressing them. As highlighted in the chapters that follow, the implications of recognizing the additional impacts of forests on climate stability beyond the carbon cycle suggest a broadening of climate policy frameworks to include biophysical pathways, as well as a broadening of constituencies influencing land-use policy to include those concerned about issues such as international conflict, human health, and agricultural productivity.

A FRAMEWORK FOR ANALYZING POLICY GAPS

Analyzing the policy implications of the additional impacts of forests on climate stability beyond the carbon cycle is a challenging task due to the fact that the biophysical effects of forests vary across scales and latitude as well as due to some remaining scientific uncertainties. Nevertheless, the scale and direction of those impacts is sufficiently clear to inform policies to capture the full range of forests' benefits for climate mitigation and adaptation. Further, those impacts have implications not only for policy arenas that focus on forests or climate change but also for other policy arenas that focus on sectors such as water, agriculture, and health.



This section introduces a framework for delineating the biophysical scope of the impacts and geographic scale of the policy implications treated in this report. The framework is also helpful for identifying relevant policy arenas, as well as for revealing analogous policy challenges for which effective approaches have been developed.

What Is the Scope of the Analysis?

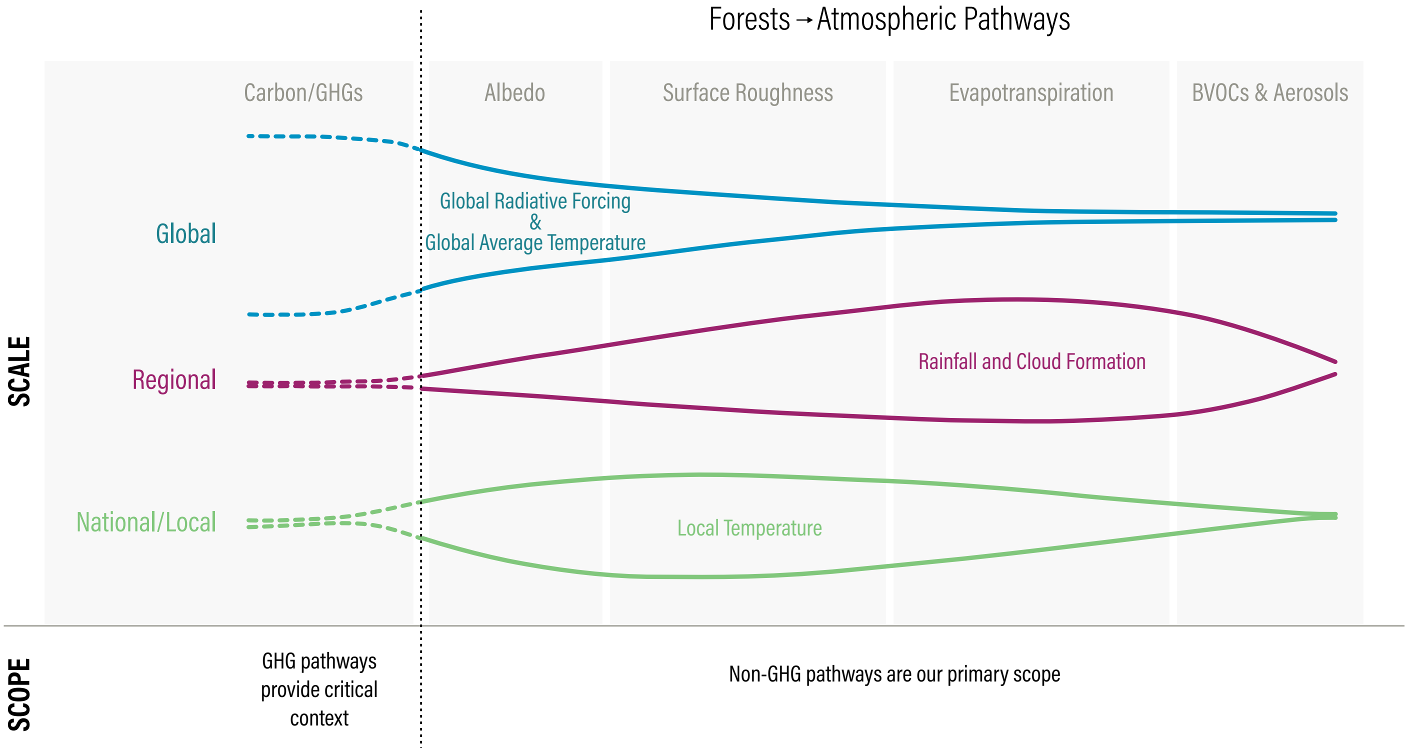
We define the scope of the analysis to be biophysical pathways through which forest cover and forest cover change affect climate stability. While we touch on the role of forests in the global carbon cycle, we give greater relative emphasis to biophysical pathways, which have received much less policy attention. It should be noted that this scope, which takes as an entry point how forests and forest cover change affect the atmosphere, is a subset of all interactions between forests and the atmosphere, as the latter would also include all the ways that the atmosphere affects forests.

We selectively include in our analysis feedback loops (i.e., when forest cover change affects the atmosphere, which in turn affects the remaining forest) and the additive effects of forest cover change and overall global warming due to forest and nonforest-related causes. However, we do not include other processes through which changes in the atmosphere can affect forests, such as forest dieback due to acid rain, except as a policy analogue from which to draw inspiration for solutions.

How Do We Decide What to Focus On?

The breadth of potential policy implications is vast, spanning multiple sectors and scales. To focus our analysis on a few of the most significant biophysical impacts of deforestation on climate stability, we assess what the science tells us about the direction, magnitude, and certainty of the effects of each of the biophysical pathways selected for review across three scales (global, regional, local/national). We group and analyze these biophysical pathways in four top-level categories, without separating out some critically important interactions at this same level of structural organization. For example, cloud formation is affected by forests through all four of the other significant biophysical pathways and their interactions, so it is not addressed separately but rather considered as an emergent phenomenon.

FIGURE 1.1 | The Relative Significance of the Various Pathways through Which Forests Affect the Atmosphere Vary by Scale



Notes: GHG = Greenhouse gas: BVOCs = biogenic volatile organic compounds. Note that some processes—such as cloud formation—largely emerge from the four focal biophysical pathways and their interactions and are not represented here as distinct pathways.

Source: Authors.

As detailed in Chapter 2, forests' biophysical effects may vary in intensity by latitude and background climate. For example, the net biophysical effect of forest cover in the boreal zone is local warming, as snow cover reflects more sunlight than tree cover, and lower levels of incoming solar energy (compared to midlatitudes) drives less cooling from evapotranspiration. However, because current rates of deforestation are being experienced largely in the tropics, we give relatively more attention to impacts in tropical regions.

This analysis enables us to select pathway-scale clusters where the impacts of forest cover change on climate stability are likely to be particularly significant, and subject those to further analysis of their policy implications. For example, deforestation in the major tropical forest basins could disrupt rainfall patterns essential to agricultural systems that currently produce food for tens of millions of people.

Accordingly, we have chosen to highlight the role of forests in terrestrial moisture recycling as an illustrative example of the regional-scale policy implications of forest loss.

Figure 1.1 provides a coarse heuristic model of the most significant pathways through which deforestation affects climate stability at different scales, the pathway-scale clusters we have chosen for deeper policy analysis in each chapter, and the scope of our analysis. The vertical thickness of the "zone of relevance" for each policy scale (global, regional, and national/local) where it crosses each forest-atmospheric pathway represents the relative significance of that process at that scale. For example, surface roughness has a large impact on local temperature and is thus a highly significant process at the national/local policymaking scale; while at the regional

policy scale, cloud formation and rainfall are critical impacts that are most directly influenced by the biophysical process of evapotranspiration.

How Do We Apply a Policy Lens to the Science?

The next step is to translate what the science is telling us about how forests affect the climate via biophysical pathways into specific implications for policy. Here, we recognize that it's not only the forest-climate interactions that are scale-dependent; the interests of policymakers and the institutions available to them through which to take action are scale-dependent as well.

For example, a climate policymaker operating at the global scale may think of the world as divided into mitigation and adaptation. On the mitigation side, they are interested in the degree to which biophysical pathways amplify or dampen the effect of GHG emissions on global warming, and whether such effects are sufficiently significant to merit adjustment in current policy frameworks such as REDD+. On the adaptation side, the global climate policymaker is concerned about the increased variability and extremes in temperature and rainfall in many places around the tropics as a result of deforestation's biophysical effects. Their interests vis-à-vis adaptation are to have a better understanding of how much climate "weirding" or risk exposure is due to these newly understood impacts on the distribution of energy and water from forest cover change vs. the impacts of increased GHGs in the atmosphere, and whether or not they imply different approaches to adaptation policy and finance.

By contrast, a local policymaker such as a mayor or district head at the forest frontier in the tropics may be most concerned about agricultural productivity and human health within his jurisdiction. Their interest in the local biophysical climate impacts of deforestation within that area is much greater than their interest in the GHG impacts of the same amount of deforestation, as the ratio of local biophysical effects to the broader GHG effects of deforestation is greater by several orders of magnitude. And indeed, the impact on local temperatures will be much larger than the impact via change in GHG concentration in the atmosphere—and far more noticeable by the people on the ground experiencing them.

In between the global and the local are a range of policymakers—provincial governments, national governments, and various regional organizations—that operate at the scale of subglobal jurisdictions. Compared to a locale on the forest frontier, the biophysical impacts of deforestation in such jurisdictions are averaged across a larger physical area—but the GHG impacts remain the same. Although the average impacts across a country or province might be small, such policymakers are interested in the large spatial variation in biophysical impacts within and beyond their jurisdictions—for example, that agricultural lands on the forest frontier will be hit hard by forest loss, and that the impact on rainfed agriculture 500 km away might be sufficiently large to trigger conflict with neighboring jurisdictions. Understanding these impacts could lead policymakers to integrate the interests of other sectors such as agriculture and health into land-use planning, as well as to invest more resources in regional cooperation.

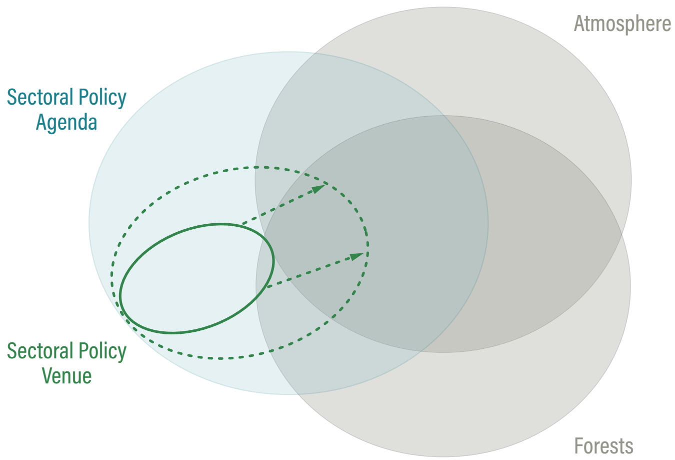
To recognize these different interests from global to local levels, we start by mapping selected biophysical impacts of deforestation onto policy agendas and venues at the relevant scales and identifying existing governance mechanisms through which they might be addressed. We also look for policy analogues that might suggest relevant models for institutional innovation.

Figure 1.2 provides the generic Venn diagram structure we use to overlay policy agendas and specific policy venues on top of the biophysical pathways defined as being within our scope. In each Venn diagram two gray circles represent “atmosphere” and “forests” as physical spaces that are of policy concern and subject to human management, with their overlap representing physical processes by which forests and atmosphere interact—and which may also be subject to policy concern and management. A large blue circle represents a sectoral policy agenda that touches on forests and the atmosphere, such as “climate” or “agriculture.” A green oval represents a sectoral policy venue that seeks to address that agenda through policymaking—for example “the UNFCCC” as a policy venue addressing the climate agenda. Finally, dotted lines represent areas where expanding the scope of a specific policy venue or process would help to fill a gap and “cover” forest-climate interactions that are currently ignored.

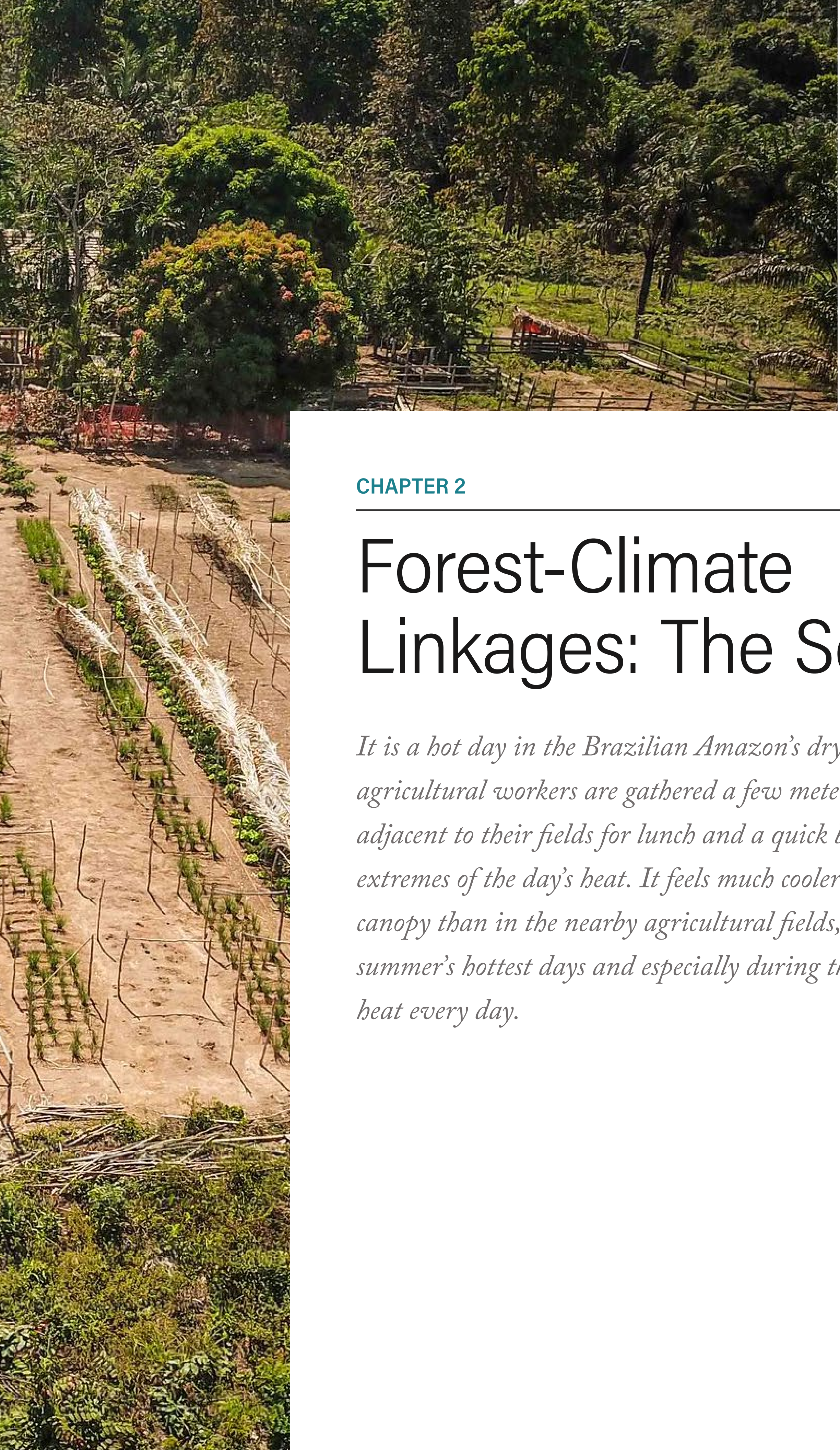
We present the results of several such analyses (and associated Venn diagrams) in subsequent chapters as illustrative examples of the significance of biophysical pathways for climate stability and human well-being, identify gaps in current policy and institutional frameworks, and suggest possible directions for future policy and institutional developments to address them.

We hope that our suggestions provide a glimpse of a future world in which coherent international, national, and local policy frameworks are woven together in ways that create optimal incentives across scales. In that world, global policymakers would be concerned about the local impacts of deforestation on climate stability above and beyond GHG emissions. National and subnational policymakers would be concerned about the variation of impacts across their jurisdictions, as well as on neighboring jurisdictions. And local policymakers would take into account not only local impacts but also the effects of local deforestation on people elsewhere.

FIGURE 1.2 | Generic Venn Diagram for Analyzing How Policy Agendas Could Expand to Capture Forest-Atmosphere Interactions



Source: Authors.



CHAPTER 2

Forest-Climate Linkages: The Science

It is a hot day in the Brazilian Amazon's dry season, and agricultural workers are gathered a few meters inside the forest adjacent to their fields for lunch and a quick break from the extremes of the day's heat. It feels much cooler under the forest canopy than in the nearby agricultural fields, especially on the summer's hottest days and especially during the early afternoon heat every day.

The trees, of course, provide shade—but this doesn't eliminate the sun's energy, which must go somewhere. This is the story of what happens to that solar energy in a tropical forest canopy, and what changes when the trees are removed.

The most intense sunlight hits dark green leaves high up in the forest canopy. A tree can only hold onto a small fraction of that light energy by using photosynthesis to capture carbon dioxide from the atmosphere, releasing a bit of oxygen and water in the process. It feeds itself with the energy it has stored, making sugar out of carbon, and locks some of that carbon (and energy) away for years or even hundreds of years by converting some of it into wood growth. Energy not stored chemically must be quickly dissipated—otherwise the leaves would soon wither and die in the intense tropical sun.

The darker the surface, the less light it reflects. Like any dark (or low albedo) surface, leaves turn a fair bit of the light that hits them into heat you could feel with your hand—sensible heat—*which radiates off their surfaces like the waves of heat rising off a blacktop road. The amazing surface complexity of the forest canopy distributes incoming sunlight and the radiating heat it creates when hitting dark leaves through a much greater volume of space than if the leaves were simply lying on the ground in a single layer. The heat rises (or convects) through this canopy volume. The canopy's surface roughness also interacts with passing winds to create* turbulence—*like boulders in a river causing chaotic swirls and spray—which quickly mixes the convecting heat into the atmosphere above.*

The remainder of the energy hitting the forest canopy is converted into a different kind of heat—the heat it takes to speed up slow-moving liquid water molecules to more than 660 meters per second, at which point they lift off of surfaces (evaporation) or out of tiny openings in leaves (transpiration) pulling more water molecules along behind them from deep in the soil. The water and energy from this evapotranspiration move up and away from the forest canopy along with the sensible heat energy, carried by the same turbulence and convection. *This kind of heat energy remains stored in the speeding molecules of water vapor, until—perhaps tens, hundreds, or thousands of kilometers away—it is released high up in the clouds when the vapor slows down and condenses into rainfall. In the same way that your body feels cooler after a swim as water dries off your skin, evaporation and transpiration also carry heat away from leaves and forest surfaces, leaving the surface and near-surface atmosphere cooler.*

Forests also have a few more subtle tricks up their sleeves to stay cool: for example, while transpiring many trees also release chemicals that interact with the low atmosphere in a variety of ways, even creating clouds in some places that further shade the forest and surrounding ground.

When the forest is cut down to make way for an agricultural field or pasture, the story changes dramatically. As vegetation burns or rots, carbon that was stored for years, decades, or even hundreds of years in living trees enters the atmosphere—mostly as carbon dioxide, and much of it quickly—where it mixes with fossil and industrial carbon dioxide emissions and also warms the global climate.

The changes to climate caused by deforestation aren't all spread evenly around the globe in the form of greenhouse gases, however: some are highly local and regional, reverberating outward from the deforested land like ripples from a stone thrown in a pond. Just as the carbon cycle has been disrupted by deforestation, so too have the energy and water cycles, amplifying the extremes of an already destabilized climate.

Land that was once shaded from the sun by multiple layers of leaves arrayed through the forest canopy is now more exposed, with lower leaf area, more exposed soil, and less evapotranspiration. Even though the surface is likely brighter—or has a higher albedo—than the formerly dark green forest canopy, the loss in evaporative cooling outweighs the greater reflection of sunlight. The end result is that this patch of land is now warmer and dryer. The temperature has risen as an annual average and even more so in the dry season and on hot days; and daily temperature swings are more extreme.

This climate change extends well beyond the patch of land where forest formerly stood. Nearby lands are also on average warmer and dryer, above and beyond the change from greenhouse effects. The changes will be biggest adjacent to land that was formerly forested but will extend much farther. Even global average surface temperature will have risen, as forest-mediated convection and turbulence that once carried solar energy high into the atmosphere no longer do, leaving that energy hovering as heat close to the ground where people live and work. Moisture that would have flowed through trees from deep soil into the atmosphere no longer does. As a result, rainfall is diminished downwind—especially during the dry season when it is needed most, and potentially hundreds or even thousands of kilometers away if carried by continental and global circulation by the atmosphere and oceans. Even the global circulation patterns themselves that drive heat and moisture from the tropics poleward can shift when enough tropical forests are lost, changing climate patterns around the world.

The description above shows that forests, and their loss and gain, can shift climate in a multitude of ways. The remainder of this chapter explains the basic science of how this happens: the various biophysical processes and the relative size of their impacts. It also explains how these processes—while themselves universal (e.g., Ellison et al. 2012, 2017)—vary systematically across the globe, in particular with latitude. The above story about a tropical forest would be different in the boreal zone in some important ways.

We start with a brief summary of well-understood forest-climate linkages through GHG pathways; cover the emerging science of forests' climate impacts through biophysical pathways involving water and energy exchanges and aerosol emissions in greater depth and detail; and then discuss the net impacts across both GHG and non-GHG effects.

SUMMARY OF GLOBAL FOREST-CLIMATE LINKAGES VIA GHG PATHWAYS

The primary focus of this report is the policy implications of the interactions between forests and climate that involve recycling of moisture and energy. However, it is critical to first understand forests' role in the carbon cycle as both a sink and a source of atmospheric carbon dioxide, the most important of the (GHG) pathways through which forests affect the climate. We take a brief detour here to review these processes and their scale, providing context and a comparative benchmark for the discussion of biophysical and aerosol processes to follow.

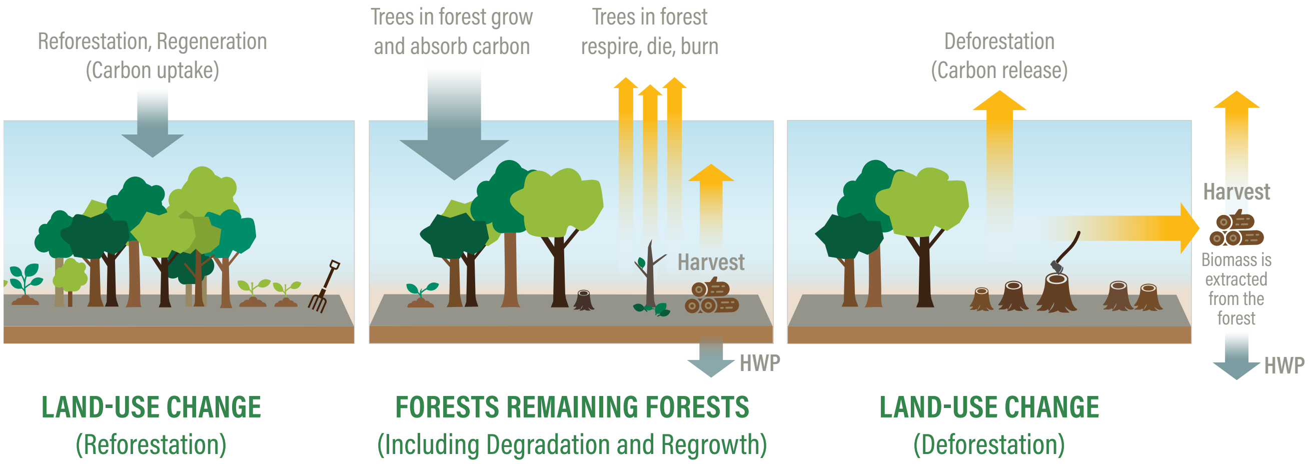
GHG emissions from land include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Most land emissions of methane (~89 percent) and nitrous oxide (96 percent) are from agriculture rather than Forestry and Other Land Use (FOLU) (IPCC 2019b); the FOLU sources include savanna burning, open burning from forest clearing, and drained peatlands and peat fires (Ciais et al. 2013). Most inventories of forest emissions only account for CO_2 emissions. In this report, we focus primarily on CO_2, the predominant GHG emission from forests.[1]

BOX 2.1 | Accounting for Emissions and Removals from Land

To understand the carbon dioxide (CO_2) emissions and removals from land use and land-use change, scientists divide land into six categories based on the predominant "use" or state of the land (e.g., forest land, cropland, grassland, wetlands, settlements, and other land). Emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) are estimated from a range of sources, including agriculture. Setting aside agriculture, the rest, forestry and other land use (or FOLU, which is added to agriculture as AFOLU) is then further subdivided. Emissions or removals over a period of time from land that is in the same category at the beginning and end is calculated (these are collectively called "land-use" emissions), and then from land that has shifted from one category to another ("land-use change" emissions and removals). The emissions and removals from "land converted to forests" and "forests remaining forests" are calculated separately as "forestry," which takes into account large carbon flows when land is still considered to be "forest" even when completely cleared of trees, and the complexities arising from timing of emissions that depend on the end use of harvested wood (e.g., carbon from biomass burned for energy enters the atmosphere almost immediately, while timber used in buildings does not). Together, these categories—previously identified as land use, land-use change, and forestry (or LULUCF)—are now identified as FOLU emissions and removals.

If we look more closely at just those parts of FOLU emissions that are related to forest processes (Figure B2.1), "Forestry" emissions (from forests remaining forests) include *uptake* of carbon from the atmosphere as forests grow, and carbon release from tree mortality, biomass burning, and the eventual breakdown or disposal of harvested wood products (HWPs). When land use changes from nonforest to forest through active reforestation or more passive regeneration, the primary impact is slow and steady carbon uptake for decades. Land-use change in the other direction—from forest to nonforest, is deforestation—with large immediate "pulse" releases of carbon from biomass that burns or breaks down quickly, and slower "committed" releases from HWPs, soil organic matter loss, and biomass breakdown.

FIGURE B2.1 | Forest-Related Emission and Sequestration Processes



Note: HWP = Harvested wood products.

Source: Federici et al. 2017.

As humans have been digging up and burning fossil fuels over the past few hundred years, the concentration of CO_2 in the atmosphere has increased, but only about half as fast as we have emitted it. Earth's ecosystems have been a buffer for the atmosphere: almost a quarter of human-caused CO_2 is absorbed by oceans (causing acidification and other problems), while more than a quarter is passively absorbed by forests and other vegetation and soils—about 11–12 billion tons every year.[2]

On top of this background process of land helping reduce atmospheric carbon are overlaid changes in humans' land use that cause the release of carbon in the opposite direction. Humans have been expanding our footprint across the earth's surface—human use directly affects more than 70 percent of global land, with one-third of land's potential production used for food, feed, fiber, timber, and energy (IPCC 2019b). Box 2.1 describes the accounting system used for these land-based emissions and removals.

In recent decades, land has been a significant source of *anthropogenic* or human-caused emissions even while it has been passively absorbing some of our fossil emissions. Agriculture, forestry, and other land use (AFOLU) contributes about 12 billion tons of CO_2 equivalent (eq) per year net, or 23 percent of total anthropogenic GHGs,[3] of which just over half is methane and nitrous oxide from agriculture.

The other half—the FOLU portion in global emissions accounting (~11 percent of GHG emissions)[4]—is a deceptively small number, as it subtracts a large sequestration of CO_2 from the atmosphere in healthy growing forests and in reforested areas from a very large source of CO_2 emissions from degrading forests and deforestation into a single *net* change. While the net number can be estimated more accurately (see, e.g., Xu et al. 2021; Jia et al. 2019, 156; Olsson et al. 2019, 369), the gross numbers are bigger and more relevant for understanding mitigation potential from land use, and thus for policymaking (Seymour and Busch 2016; Griscom et al. 2017; Houghton and Nassikas 2018)—and are improving in accuracy through recent research (Canadell et al. 2021, 221). The left side of Figure 2.1 illustrates these gross and net annual FOLU emissions in the context of global CO_2 emissions from all sources—starting with about 16 gigatons (Gt) CO_2 of gross FOLU CO_2 emissions per year, subtracting approximately 10.5 Gt CO_2 gross FOLU sequestrations per year, resulting in about 5.5 Gt of net FOLU CO_2 emissions per year—which is about 15 percent of the total 40 Gt CO_2 anthropogenic emissions per year.

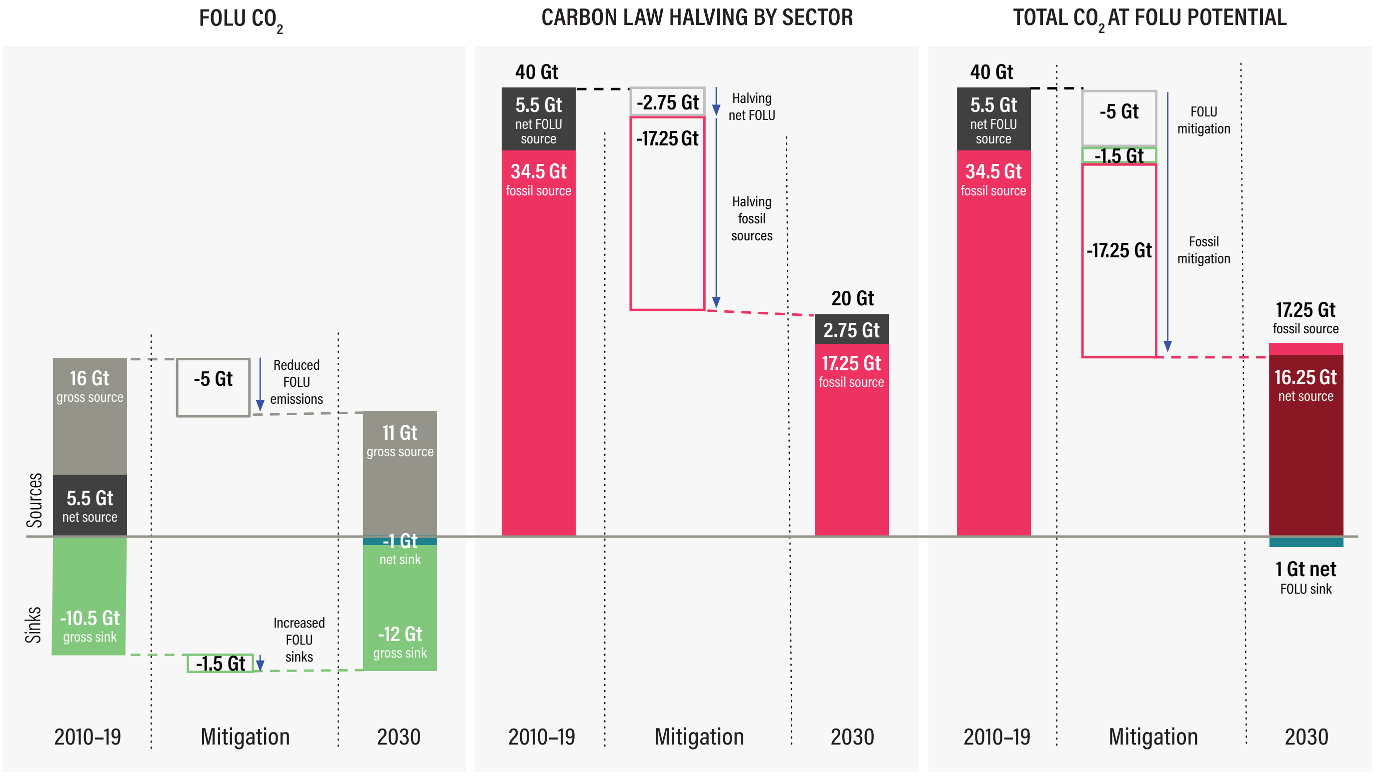
Reforestation is dominated by recovering forests largely in the temperate Northern Hemisphere, with a mix of abandoned farmland returning to forests such as in the United States, and large-scale active reforestation programs such as those in China. It is also largely the northern countries where forestry (forest remaining forest) is a net carbon sink through recovery and growth, rather than a net source through forest degradation. Gross FOLU sequestrations from these processes globally may be as high as 10–15 billion tons of CO_2 per year (Jia et al. 2019, 152, 157; Friedlingstein et al. 2020; Canadell et al. 2021).

By contrast, deforestation is currently the dominant land-use change process in the tropics, largely due to conversion of land from forests to agriculture. While there is a significant area of recovering secondary forests, their regrowth is slow, and the total carbon sequestration is much smaller than the emissions from loss of old-growth forests. For example, Smith et al. (2020) find that secondary forest recovery in Brazil offsets less than 10 percent of the emissions from old-growth forest loss since 1985. The FAO estimates that 10 million hectares of forest—mostly natural forests, and mostly in the tropics—have been lost annually from 2015 to 2020, compared to 5 million hectares of forest expansion—mostly in the north, and mostly plantations and planted forests (FAO 2020). Global gross FOLU emissions (including deforestation, forest degradation, and significant emissions from peatland degradation most extensively accounted for in Southeast Asia) may be as high as 16–20 billion tons of CO_2 per year or higher (Jia et al. 2019, 152, 157; Canadell et al. 2021).

A change in land use from forests to agriculture has more climate impact than just the immediate and committed emissions. The agriculture that most frequently replaces forests is almost always on the other side of the ledger—a GHG source rather than sink. And a third GHG-warming impact from deforestation must also be added: the lost forest carbon sink. Healthy forests—even very old and undisturbed forests—continue to absorb carbon from the atmosphere, so every hectare of deforestation is not only an emission but also the loss of future sequestration (Maxwell et al. 2019). In fact, growing and mature forests are some of the few globally significant negative *feedback cycles* that naturally slow down climate change, as higher CO_2 in the atmosphere along with nitrogen deposition have led to increased passive forest uptake. The mitigation potential from avoiding deforestation and maintaining and enhancing removals is thus additive.

The left panel of Figure 2.1 illustrates the primarily forest related FOLU CO_2 components of this cost-effective AFOLU mitigation potential. The panel illustrates the

FIGURE 2.1 | Global Forest and Other Land Use CO_2 Emissions and Sequestrations



Notes: Left panel is FOLU CO_2 emissions, sequestrations (sinks), and mitigation at cost-effective ($100/ton) levels; center panel is a mitigation scenario of halving both FOLU and non-FOLU emissions; right panel is a mitigation scenario of halving fossil CO_2 emissions combined with cost-effective FOLU mitigation. Within each panel, the left column represents 2010–19 average annual historical emissions and sequestrations, the center column represents the mitigation scenario, and the right column represents the remaining 2030 annual emissions and sequestrations after mitigation. Authors' calculations from Canadell et al. 2021; IPCC 2019b; and Roe et al. 2021. Numbers may not add up due to rounding.

Source: Authors.

5 Gt of opportunity to reduce gross FOLU CO_2 emissions from about 16 Gt per year to about 11 Gt per year largely by slowing tropical deforestation, while also illustrating an additional 1.5 Gt CO_2 of opportunity to increase gross sequestrations largely from afforestation and reforestation. Reducing gross FOLU CO_2 emissions and increasing gross FOLU sequestrations would together shift net FOLU emissions by 6.5 Gt CO_2 per year total: from a 5.5 Gt CO_2 per year net source, to a 1.0 Gt per year net sink. The center panel illustrates a mitigation scenario if both the FOLU and non-FOLU sectors cut CO_2 emissions in half by 2030 according to the "Carbon Law" (Rockström et al. 2017), resulting in total net CO_2 emissions of 20 Gt per year in 2030. The right panel illustrates a mitigation scenario resulting from a halving of fossil CO_2 while also achieving 6.5 Gt CO_2 per year of cost-effective FOLU mitigation—resulting in total net CO_2 emissions of 16.25 Gt per year in 2030. In the range of decadal emissions mitigation represented in the figure, 6.5 Gt CO_2 per year of mitigation from FOLU would represent in the range of 27 percent (6.5 Gt out of 23.75 Gt total mitigation in the right panel) to 33 percent (6.5 Gt out of 20 Gt total mitigation in the center panel) of the mitigation required to keep 1.5°C within reach (authors' calculations based on Roe et al. 2021; Canadell et al. 2021; IPCC 2019b).

BIOPHYSICAL FOREST-CLIMATE INTERACTIONS

While the GHG pathway is a critical consideration with respect to forest-climate interactions, increasing study has expanded our understanding of the *biophysical mechanisms* through which forests impact climate at local, regional, and global scales. Biophysical mechanisms are those which involve biologically mediated land-surface properties and exchanges, including albedo (or reflectivity), surface roughness, and evapotranspiration, all of which affect the amount and forms of water and energy transfer between land, the biosphere (living organisms), and the atmosphere. These mechanisms contrast with *biogeochemical mechanisms,* which involve biologically mediated changes in the form and energy content of elements and compounds, for example when plants capture and store solar energy by converting lower-energy CO_2 into higher-energy sugars through photosynthesis. All of these mechanisms are at play in every forest in the world, even though their relative effects vary significantly. This section seeks to summarize and simplify this complex and often overlooked field, largely as explored in an overview of recent significant advances published in the scientific literature (Lawrence et al. 2022).

Biophysical Mechanisms

Three direct biophysical mechanisms of forests have significant influence on the recycling of energy and water at multiple scales: their albedo, or reflectivity; the evaporation and transpiration of water off and through their leaves; and the uneven and complex physical structure of the forest canopy itself. Forests also influence the climate indirectly as some of the compounds they emit alter the way the atmosphere holds and releases energy and water. These processes also combine and generate feedbacks—both positive and negative—which further amplify or dampen forests' initial impact on energy and water recycling at a range of scales. Figure 2.2 represents these four mechanisms of interaction and some of their feedbacks.

Surface Albedo

Forests' dark green surfaces absorb a larger fraction of incoming solar energy than the brighter surfaces that typically replace them following deforestation and than those that are typically adjacent to or beneath them—such as bare soil; row crops; grasslands; and, in higher latitudes, snow. This low albedo (or reflectivity) of forests has a direct impact on the global energy balance between space and the Earth-atmosphere-ocean system: a "*radiative forcing*." The global radiative forcing of forests' low albedo usually pushes in the opposite direction of forests' carbon/GHG impact.

Evapotranspiration

As described in the introductory story above, some of the solar energy hitting a forest converts liquid water into water vapor (carrying energy as *latent heat*) through evaporation and transpiration, together termed evapotranspiration. Forests are incredibly efficient at this, due to trees' deep roots and high leaf area. Thus, in addition to redistributing heat in the atmosphere, standing forests are also strong regulators of rainfall. Studies generally agree that rainfall decreases in deforested areas, although the effect on nearby precipitation changes can be complex—depending on the size of the area of deforestation, relative location and prevailing winds, and the overall importance of forests in moisture recycling at various places and times (Lawrence and Vandecar 2015).

As described further in Chapter 4, upwind forest cover has been shown to affect rainfall in areas downwind (Keys et al. 2016). Forest cover changes can redistribute rainfall and alter its seasonality and extremes. Of course, forests also influence the amount and flow of surface and subsurface water, acting as a "sponge" (Peña-Arancibia et al. 2019) that limits the impact of extreme rainfall events and flooding, and regulates river flows at large scales (Lawrence et al. 2022). These forest-surface water processes have been studied for decades and are not considered further in this report, which is focused on forests' interactions with the atmosphere.

Deep roots allow trees to transpire even during droughts and in dry seasons; evapotranspiration from forests can thus provide a critical source of water that feeds rainfall downwind, even at great distances (Ellison et al. 2012). In the Amazon Basin, tree-transpired rainfall accounts for up to 70 percent of regional rainfall at the end of the dry season (Staal et al. 2018). Deforestation of the southern Amazon Basin of Brazil beginning in the late 20th century has thus lengthened the dry season (Lawrence et al. 2022). The importance of forests in recharging atmospheric moisture content varies spatially and across different regions but can tie together the land-use patterns in one area to rainfall—and thus agricultural productivity—at great distances (see terrestrial moisture recycling review in Chapter 4).

Surface Roughness and Wind Circulation

The physical structure of a forest is a third source of biophysical influence on climate. The canopy surface is rough and complex, interacting with passing winds and with rising latent and sensible heat to create turbulence that mixes surface air with air in the low atmosphere. The loss of surface roughness and complexity from deforestation can increase horizontal wind speeds close to the land surface, and reduce the mixing of near-surface air, leaving the land surface dryer and warmer. Changes in the vertical movement of heat and moisture following deforestation generally reduce rainfall, but *edge effects* and changes in convection patterns from small-scale deforestation (tens of kilometers) can lead to very local increases in precipitation as well (Bonan 2019; Werth and Avissar 2002).

As discussed above, water vapor released by forests moving into the atmosphere as a result of above-canopy turbulence can travel great distances before it condenses as rain and releases its latent heat—as much as 500–2,000 km away in the tropics, and 3,000–5,000 km in the temperate zone (Tuinenburg and van der Ent 2019). This moisture is carried by global-scale circulation patterns that are themselves affected by the biophysical properties of forests. High levels of solar energy in the tropics result in high levels of latent and sensible heat entering the atmosphere—especially above forests—which then travels around the earth. Model experiments that remove forests result in large-scale circulation changes—for example, changes in the jet stream and Asian monsoons, among others. Thus, a change in forest cover hundreds or thousands of miles away affects not only the energy and moisture in arriving weather systems, but even from whence those systems typically arrive: the patterns of global climate themselves thus depend on the forests' biophysical albedo, evapotranspiration, and surface roughness effects.

Secondary Effects—The "Aerosols"

In addition to the three direct biophysical interactions outlined above—albedo, evapotranspiration, and surface roughness—forests also produce a wide range of particles and compounds that alter energy and water transmission in the atmosphere directly, through chemical and physical processes, and by regulating cloud formation.

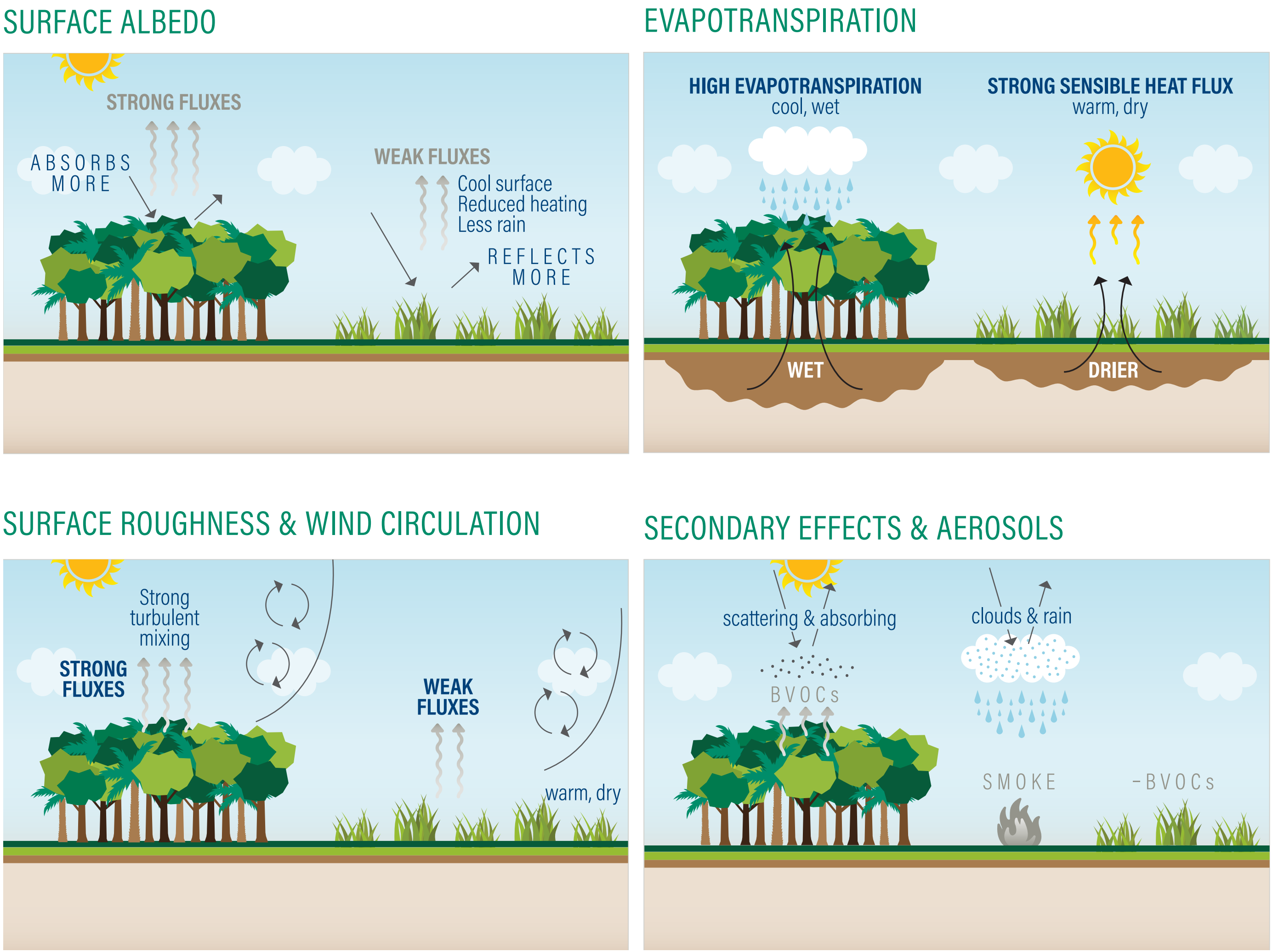
First, these include biological products such as bacteria, fungal spores, and pollen (*primary biological aerosol particles* or PBAPs), which have various effects on atmospheric albedo and surface temperature of unclear importance.

Second, forests—especially broadleaf forests of the tropics—also produce quickly vaporizing carbon-based chemicals (*biogenic volatile organic compounds*, or BVOCs), which affect the atmosphere and climate in complex ways. For example, *isoprene* is a chemical released by broadleaved trees in warm weather, while terpenes released by conifer trees for protection against pathogens and herbivores are responsible for the sharp, sweet, and refreshing aroma of pine trees. BVOCs released by trees increase the lifetime of methane in the atmosphere and lead to the formation of ozone—both GHGs—and thus have GHG-related climate-warming effects, even though they are not themselves GHGs. BVOCs also regulate the concentration of highly reflective *secondary organic aerosols* (SOAs), which increase atmospheric albedo and alter the release of heat inside clouds, with both cooling and warming effects.

Together, these various particles and compounds (PBAPs and BVOC-regulated SOAs) affect the formation of clouds—including their presence or absence, their altitude, and their reflective properties. The increased water vapor from forest evapotranspiration can also directly impact cloudiness and albedo by supporting cloud formation over forests, both alone and in combination with aerosol effects. The cooling effects of additional cloud formation from forests can offset some of the warming from forests' low albedo.

Research on the net effects of BVOCs at the local and global scales is ongoing, as it is difficult to tease apart the effects of these various pathways on clouds. What is clear is that the strongest effects are in the tropics, where increased cloud albedo offsets a significant portion of the warming effect of low-albedo forest canopy.

FIGURE 2.2 | Biophysical and Aerosol Forest-Climate Pathways: Mechanisms and Impacts



Note: BVOCs = biogenic volatile organic compounds.

Source: Wolosin and Harris 2018.

Local Biophysical Effects by Latitude

The net effect of biophysical forest-climate interactions depends on the amount of solar energy available and the supply of moisture available for evapotranspiration, both of which depend on the prevailing background climate of any particular place on the planet. This section summarizes these effects *excluding* greenhouse warming; the subsequent section adds the two types of effects together.

Four patterns of place-based effects are particularly significant. First, recent studies show that forest cover change has the greatest local temperature impacts in dry regions such as the western United States and the Loess Plateau in China. Deforestation leads to relatively more warming, and forestation to relatively more cooling, in drier areas (Lawrence et al. 2022), because there is a much greater difference in evapotranspiration between open lands and forested lands in dry areas than in moist areas. Second, higher typical cloudiness in an area will moderate forests' albedo warming as clouds reflect more sunlight than the canopy surface. Third, in relatively colder locales such as the forests in Canada and northern Europe, dark, low-albedo forest canopies will more often mask more reflective snow cover; forest cover loss in these areas results in greater albedo changes with more relative biophysical cooling than at lower latitudes. And finally, in coastal areas, temperatures tend to be moderated (not as cold in winter, and not as hot in summer) by proximity to the ocean, which may extend growing seasons and increase the cooling effect of coastal forests around tropical cities by virtue of increased evapotranspiration throughout the course of a year (Lawrence et al. 2022). While these place-based idiosyncrasies in background climate are significant, latitude nevertheless drives a strong global gradient in net biophysical effects overlaying all of them.

BOX 2.2 | Biophysical Traits and Forestry

Much of the scientific literature cited in this section focuses on forest cover change rather than changes in the structure or management of forests that remain forests. This is largely because the signal of biophysical pathways is easier to detect when the forest change is more dramatic. But it doesn't mean albedo, surface roughness, evapotranspiration, and aerosol-based processes are irrelevant in managed forests. For example, Meunier et al. (2022) investigate the combined effects of increased liana prevalence across the tropics through both biomass and optical pathways.[a] They find that lianas (such as rattan) reduce tree and ecosystem gross primary productivity and shift the forest albedo. This example shows that tropical silvicultural practices, such as cutting lianas, could have significant global climate impacts through both carbon[b] and biophysical pathways. The biophysical changes from deforestation are large, relatively immediate, and well estimated—and thus receive more attention in the scientific literature and this report. But they are at play in all of the forest processes outlined in Box 2.1 and Figure B2.1.

Sources: a. Meunier et al. 2022; b. Finlayson et al. 2022.

Tropical Zone

More sunlight in the tropics provides more energy to drive heat and water transfers away from the earth's surface, and the net biophysical effects of forests are dominated by cooling through evapotranspiration. Studies of adjacent forest and field sites, and of before/after forest cover change at the same site, all show consistent local cooling effects of forests in the tropics of about 1°C in annual average temperature (Lawrence et al. 2022, Figure 1, SI Table S2). However, annual averages conceal the dramatic increases in local daytime high temperatures that have been documented following deforestation in the tropics: 4.4°C when forests are converted to open land; 6.2°C when primary forests are converted to pasture; and 7.6°C when primary forests are converted to cropland (Schultz et al. 2017 and Senior et al. 2017, as cited in Lawrence et al. 2022, SI S3). Across years, seasons, and days, forests moderate the heat of the tropics, cooling things down the most during the extreme heat of the day. Box 2.2 addresses the potential impacts of changes in forest management, short of deforestation.

Boreal Zone

At high latitudes, the net biophysical temperature effect of forests is on average in the opposite direction of that in the tropics: forest cover in the boreal results in net biophysical warming, rather than net biophysical cooling. This is because there is much less incoming sunlight, so the energy available to drive forest evapotranspiration and vertical mixing is lower, and the warming effect of the dark, low-albedo canopy dominates over evapotranspirative cooling. This is particularly the case in the winter and spring when snow is frequently the exposed surface when forests disappear. Various estimates of average annual temperature change from forests in the northern boreal region average just under 0.5°C of warming from forests (Lawrence et al. 2022, Figure 1, SI Table S2). Seasonal and daily differences are masked by this annual average, with very slight forest cooling (0.5°C) in the summer and more than average warming (up to 3°C) in the winter, and swings from cooling during daytime to warming at night (Lawrence et al. 2022, Figure 2, SI S3).

The local biophysical warming impact of forests is further amplified by snow and ice albedo feedbacks. When forests are removed in the boreal region, strong local cooling from bright snow reflecting more sunlight can extend the time that the surface remains snow covered, creating a biophysical positive feedback. This feedback itself will change in complicated ways as the climate warms, not only with snow loss decreasing the cooling effect of deforestation but also a trend toward darker canopies increasing the warming effect of forest presence, alongside some northward shift and contraction of boreal forests. Regardless, colder air also holds less moisture, transferring the cooling effect of forest loss to nearby water as colder, dryer air cools the ocean—and leading to a second positive albedo feedback through increased sea ice, which is much more reflective than open water.

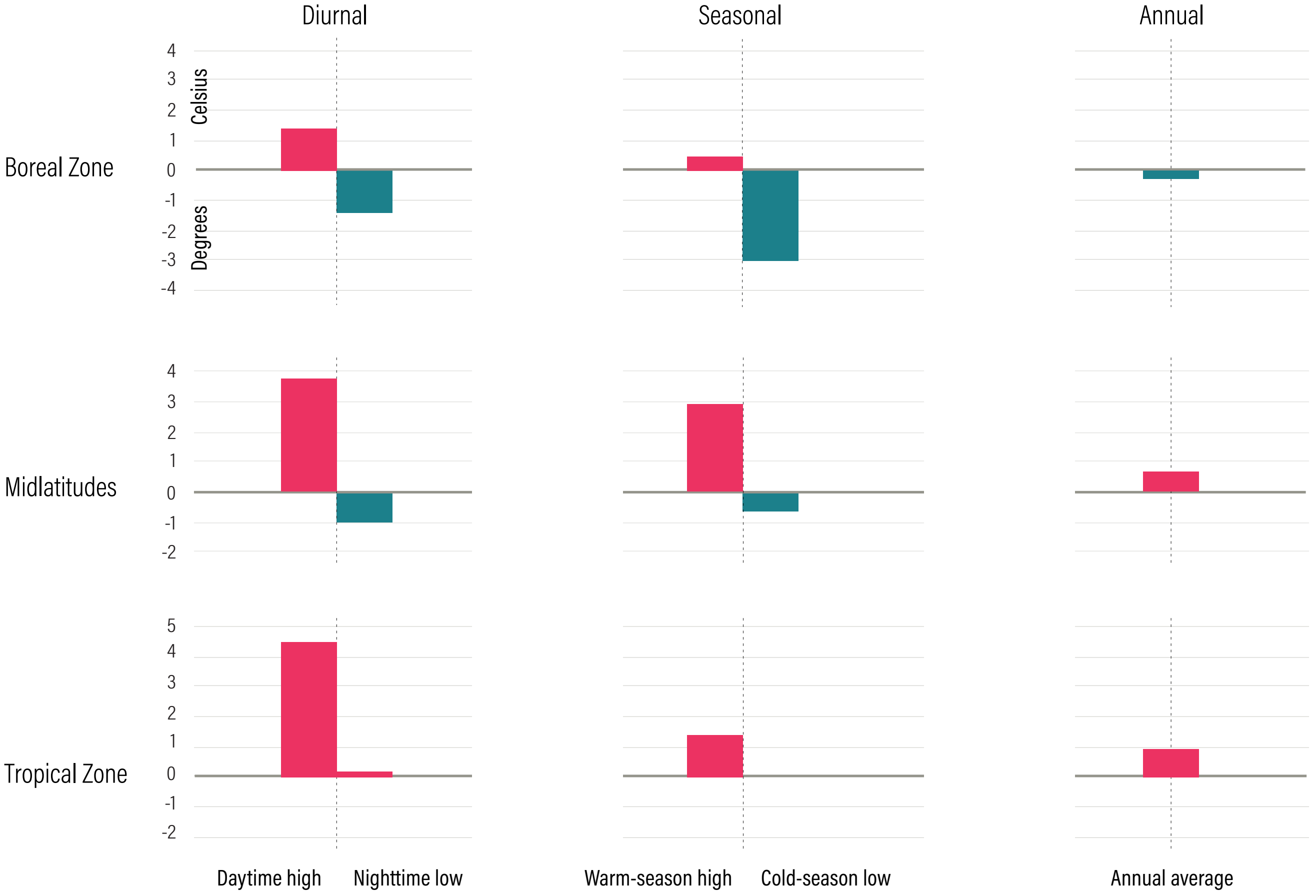
While the direction of biophysical temperature impacts from forests in the boreal zone is on average the opposite of that in the tropics (warming rather than cooling), forests in the boreal are similar to those in the tropics in the important role of *moderating extremes*. They provide some warming in the face of low average temperatures, especially during the cold season and at night when it is coldest. During the warm season and at midday, they cool instead of warm the surrounding area, again buffering against dramatic temperature swings and extremes. When forests disappear, the coldest parts of the world (and in those areas, also the coldest seasons and times of day) get colder and the warmest parts of the world (and in those areas, the warmest seasons and parts of the day) get hotter.

Midlatitudes

There is evidence that currently across the temperate zone, the average annual biophysical effect of deforestation is warming—as in the tropics, but to a lesser degree (Figure 2.3). Seasonally, forests generally provide a net cooling effect in the warm season when evapotranspiration dominates, and a net warming effect in the cold season when dark forest canopies mask snow-covered surfaces and albedo effects dominate. Again, forests moderate extremes in the zone, not just seasonally but also daily: providing a cooling effect during the day and a warming effect at night (Figure 2.3).

Perhaps more salient in this transition zone with extreme variance in radiation, seasonality, and vegetation type is to identify at what latitude the annual average of local biophysical effects shift from net cooling (as in the tropics) to net warming (as in the boreal). The shift is gradual and

FIGURE 2.3 | Local Biophysical Temperature Impacts of Forest Loss by Latitude in the Northern Hemisphere



Notes: Data from Figures 2 and 3 in Lawrence et al. 2022.

Source: Lawrence et al. 2022.

highly dependent on local background climate, with the latitude of zero-net biophysical effect in the Northern Hemisphere in the range of 30° to 56° North (Figure 2.3), a band that encompasses most of the U.S. mainland, continental Europe, China, and Japan. This transition latitude itself would be expected to shift northward with global warming.

In all three climate zones, forests' biophysical processes moderate local and regional temperature extremes and variability. This moderating role of forests has a significant economic value: recent research shows that temperature variability itself causes greater climate damage than a similar but stable change in mean temperatures would imply (Calel et al. 2020).

NET CLIMATE EFFECTS OF CO_2 AND BIOPHYSICAL PATHWAYS TOGETHER

It is relatively simple to assess the net effects of biophysical changes on local climate—at least in terms of temperature, and to some extent on rainfall. With measurements from the ground, or a tower, or even a satellite, we can compare the climate in a forest to an adjacent field; or from before a deforestation or reforestation event to after in the same location. We can average all such observations and experiments in a given area or climate zone, and the results are pretty clear: forest loss in the boreal zone mostly leads to local cooling; in the tropics, it unambiguously leads to local warming; and in the temperate zone, there is a transition from one to the other effect that depends greatly on background climate (as in the above sections), and probably happens somewhere between 30° North (the latitude of New Orleans, Shanghai, or New Delhi) to 56° North (Moscow or Edinburgh) in most places.

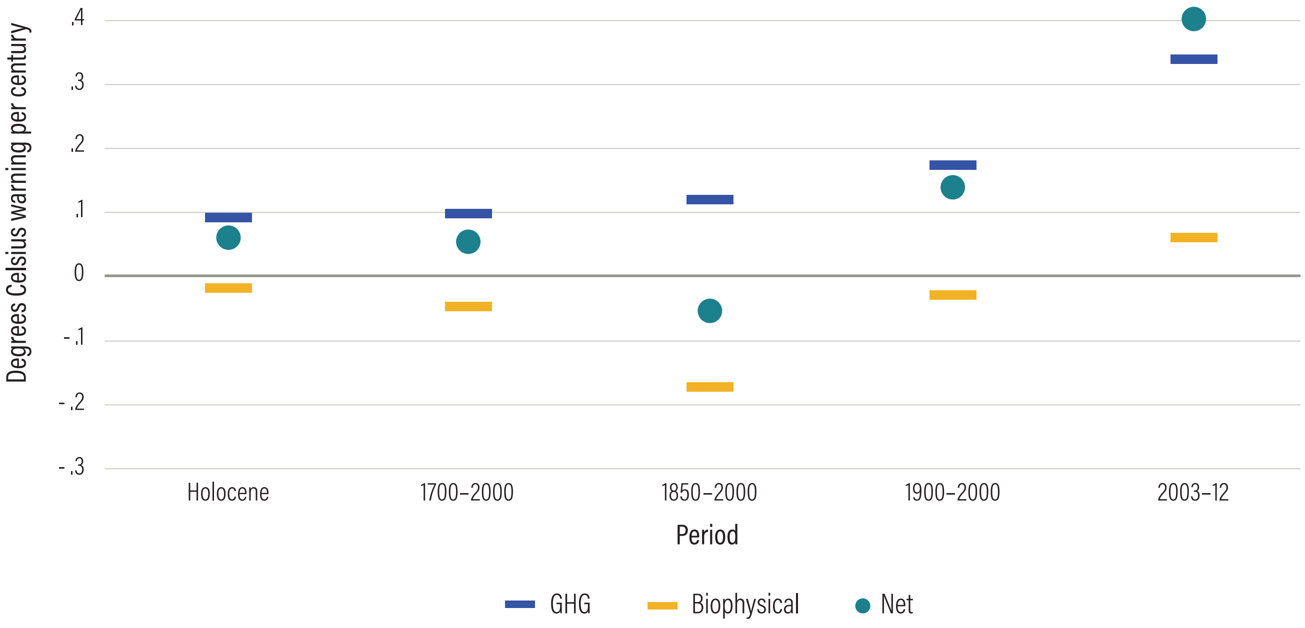
It is more difficult to both conceive of the right questions to ask, and to then accurately provide estimates, to understand the net changes in climate at broader spatial and temporal scales from all biophysical effects combined, or from biophysical and GHG effects added together. The biophysical effects of forest cover change in a single patch are locally very large (and location-dependent) but diminish with distance to become negligible when averaged over large areas; the GHG emissions or removals of the same small-scale forest cover change are practically zero at that location but are the same size and direction everywhere across the entire globe and for hundreds of years—and can thus add up. Furthermore, when scaling up across space and time, one must also shift from assessing a simple change in land use—forest to nonforest, or vice versa—to patterns of land-use change. How much forest is gained or lost, and where? Is the assessment based on historical patterns, forecasts, or a hypothetical model? What is the existing pattern of forest cover—and even of background climate conditions—when the change is assessed?

The remainder of this section explores the net effects across different scales, mechanisms, and time periods, to the extent that the existing scientific literature has developed such estimates.

Net Global Temperature Effects of Historical Global Forest Change

The effect of forest loss when forests covered much of the planet's land surface may have been different than additional deforestation occurring after that loss—the impacts of forest cover change are nonlinear. Furthermore, a majority of forest loss over the industrialization era took place in the temperate zone, with smaller net biophysical effects than would be expected from tropical deforestation. The net effect of historical forest loss thus depends on the period of time examined (Figure 2.4).

FIGURE 2.4 | Global CO_2, Biophysical, and Net Impacts of Historical Forest Loss



Notes: GHG = Greenhouse gas.
Data from Lawrence et al. 2022, Table 1. Temperature changes adjusted to per-century basis. All data points are models except for 2003–12, which is observed.

Sources: Holocene: He et al. 2014; 1700–2000: Matthews et al. 2004; 1850–2000: Brovkin et al. 2004; 1900–2000: Pongratz et al. 2010; 2003–12: Alkama and Cescatti 2016.

Most models of the global temperature effects of long-term historical land-use change patterns show biophysical cooling somewhat moderating the dominant effect of greenhouse warming from land-use change, with only one model showing that cooling exceeds warming. In the most recently available historical study of observed (rather than modeled) warming, deforestation was primarily tropical rather than temperate, and biophysical warming amplified rather than dampened greenhouse warming by ~18 percent (Alkama and Cescatti 2016). None of the modeling studies shown here included the effects of forest cover change on cloud albedo through BVOC pathways; there is evidence that including these effects would shift the biophysical temperature changes somewhat toward warming.

In short, there is good evidence that in the past, the CO_2-warming impact from forest loss was offset to some degree by the global cooling impacts due to disruptions of biophysical processes, but that offset has disappeared or even reversed as forest loss has shifted to the tropics.

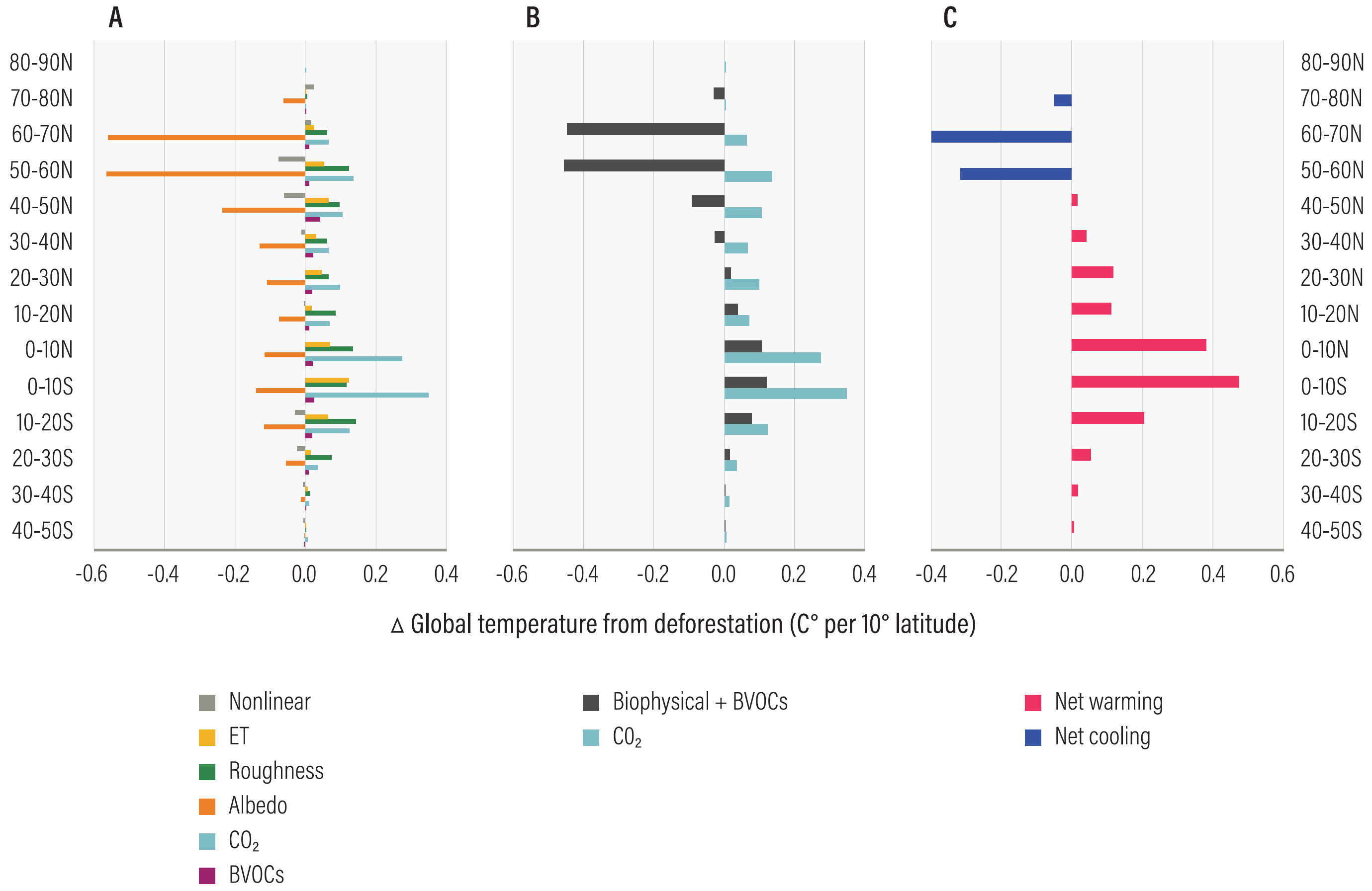
Net Global Temperature Effects of Forest Change by Latitude

The above data and models all look at historical spatial patterns and extent of forest loss to understand global temperature impacts. To examine the differences in global temperature impacts of forest loss at different latitudes, model simulations impose extreme experimental forest gains or losses in order to detect the average temperature changes and explore large-scale climate feedbacks.

A reanalysis by Lawrence et al. (2022) combines the estimates of temperature impacts by latitude from biophysical mechanisms in one of these large-scale global deforestation experiments (Davin and Noblet-Ducoudré 2010), with comparable estimates of temperature impacts from CO_2 emissions resulting from the same deforestation.

Their results provide significant new insights into the combined CO_2 and biophysical effects of large-scale deforestation on global temperature at various latitudes (Figure 2.5). They find a net biophysical effect on global temperature from forest loss from 30° South to 30° North of about half as great and in the same direction as the CO_2 effect of global warming. This suggests that in the tropics, biophysical mechanisms are effectively amplifying the global CO_2 warming effect of deforestation by about 50 percent. The net biophysical effects of deforestation in the midlatitudes (30° to 50° North) is cooling, but of a smaller magnitude than the resulting global CO_2 warming. In the midlatitudes, biophysical mechanisms are effectively dampening global CO_2 warming effects of deforestation by 40–85 percent. North of 50° N, the significant net global cooling of biophysical effects from forest loss vastly exceeds the global warming from CO_2, resulting in net global cooling.

FIGURE 2.5 | Modeled CO_2, Biophysical, and Net Impacts by Latitude of Global Forest Loss



Notes: ET = Evapotranspiration; CO_2 = Carbon dioxide; BVOCs = Biogenic volatile organic compounds.
Effect of complete deforestation on global temperature by 10° band of latitude: (a) Contribution to global temperature change by climate forcing factor. Biophysical factors are from Davin and Noblet-Ducoudré (2010), area-weighted. BVOC effects are estimated relative to albedo effects based on Scott et al. (2018). CO_2 effect is based on aboveground live biomass for each 10° latitudinal band following Baccini et al. (2017) and Walker et al. (2020); (b) Cooling or warming effects of deforestation by 10° latitudinal band (BVOCs included).

Sources: Lawrence et al. 2022.

How Significant Is Tropical Forests' Global Biophysical Cooling?

For policymakers to better understand the scale of tropical forests' global cooling effects beyond carbon, we translate the Lawrence et al. (2022) estimate of 50 percent biophysical amplification of global warming from deforestation in the tropics into an estimated GtCO$_2$-equivalent global cooling from avoided tropical deforestation. We find such global biophysical cooling would be significant in the context of global climate policy objectives.

Griscom et al. (2020) estimate that avoided deforestation in the pantropical region could achieve cost-effective mitigation of about 2.8 GtCO$_2$ per year, and a "safeguarded" maximum mitigation of about 3.5 GtCO$_2$ per year, both from 2030 to 2050.[5] With forest action in the tropical zone achieving one-half as much global average temperature cooling through biophysical pathways as from CO$_2$ alone, the additional global climate cooling benefits of these scenarios would be roughly equivalent to the cooling achieved by an additional 1.4 to 1.8 GtCO$_2$ per year over this period—that our international climate policy is currently ignoring. This scale of *additional* global cooling is approximately comparable to all of Russia's anthropogenic GHG emissions reported for 2019.

If we assume that the amplification rate of global cooling from reforestation is the same as from avoided deforestation, the global cooling benefits of forest mitigation in the tropics would be even larger. Griscom et al. (2020) estimate cost-effective and safeguarded maximum mitigation from both avoided deforestation and reforestation in the tropics at 4.0 to 4.7 GtCO$_2$ per year, suggesting an additional global biophysical cooling of 2.00 to 2.35 GtCO$_2$ per year—a scale of mitigation comparable to twice Japan's current GHG emissions.

This calculation attempts to translate the combined biophysical climate effects of forests on the earth's global average surface temperature into a CO$_2$ equivalent and requires assumptions that we know are incorrect—such as linearly scaling biophysical effects with levels of deforestation, and equivalent effects from avoided deforestation and reforestation. However, even as a very rough first approximation it should give policymakers a sense of the potential scale of forest biophysical global cooling. Additional research can and should refine this estimate.

Net Local Temperature Effects of Forest Change

The above section examines the relative *global* temperature impacts of forest change in various places and through various pathways. While these global temperature impacts are highly relevant to international and national policymakers, local policymakers would be much more interested in the net local impacts of deforestation on the climate that are actually felt by people, and that drive the health and productivity of local agriculture and ecosystems. The relative extent to which local forest changes are causing local climate changes, as opposed to changes attributable to aggregated GHG emissions from beyond their jurisdictions, will affect their sense of control over reducing the harms.

So how big are the local effects of forest cover change on temperature compared to global greenhouse warming? Lawrence et al. (2022) show that the local temperature impact of GHG warming from widescale deforestation compared to local biophysical temperature effects of deforestation is miniscule—at most one-fifth as large on an annual average basis, but usually much less—even when the GHG impacts considered are from deforestation of that location's entire 10° band of the earth (Lawrence et al. 2022, S1, Table S2).

Back-of-the-envelope calculations can also be instructive. For example, Figure 2.3 shows local temperature changes from biophysical mechanisms as a result of nearby forest loss in the tropics of just under 1°C of warming averaged over a year, but closer to 4.5°C increase in average daily high temperatures. Compared to the increase of about 0.87°C in global mean temperature, or 1.53°C increase in average land temperatures attributable to all GHG impacts—including both forest change and fossil emissions, these local biophysical temperature changes are clearly of a similar scale and significance.[6] In short, local policymakers in areas undergoing forest land-use change—especially in the tropics and the boreal zone—may have as much or more opportunity to mitigate local climate change through actions to reduce local deforestation than could be achieved by the entire global GHG mitigation effort combined.

Net Impacts of Future Forest Change

Additional uncertainties enter the picture when considering the relative and net impact of biophysical and greenhouse climate pathways from future forest cover change. For example, natural forest disturbance patterns—such as hurricanes, droughts, fires, and large die-offs from insects or other diseases—are all shifting with climate change. As land-use change pushes further into forests, there is a shift toward smaller forest patch sizes and an increase in total forest area that is close to forest edges, both of which reduce the health of remaining forests and their carbon uptake. The carbon effects of processes such as these are not fully represented in current climate models.

The biophysical forest-climate interactions summarized above will also shift as the climate warms. In a future warmer climate, weakening snow and ice feedbacks in the boreal zone would diminish the biophysical cooling effects of forest loss. Changes in tree physiology with rising CO_2—such as an ability to release less water for a given amount of photosynthesis, or changes in BVOC production—may also shift the balance between carbon and biophysical effects.

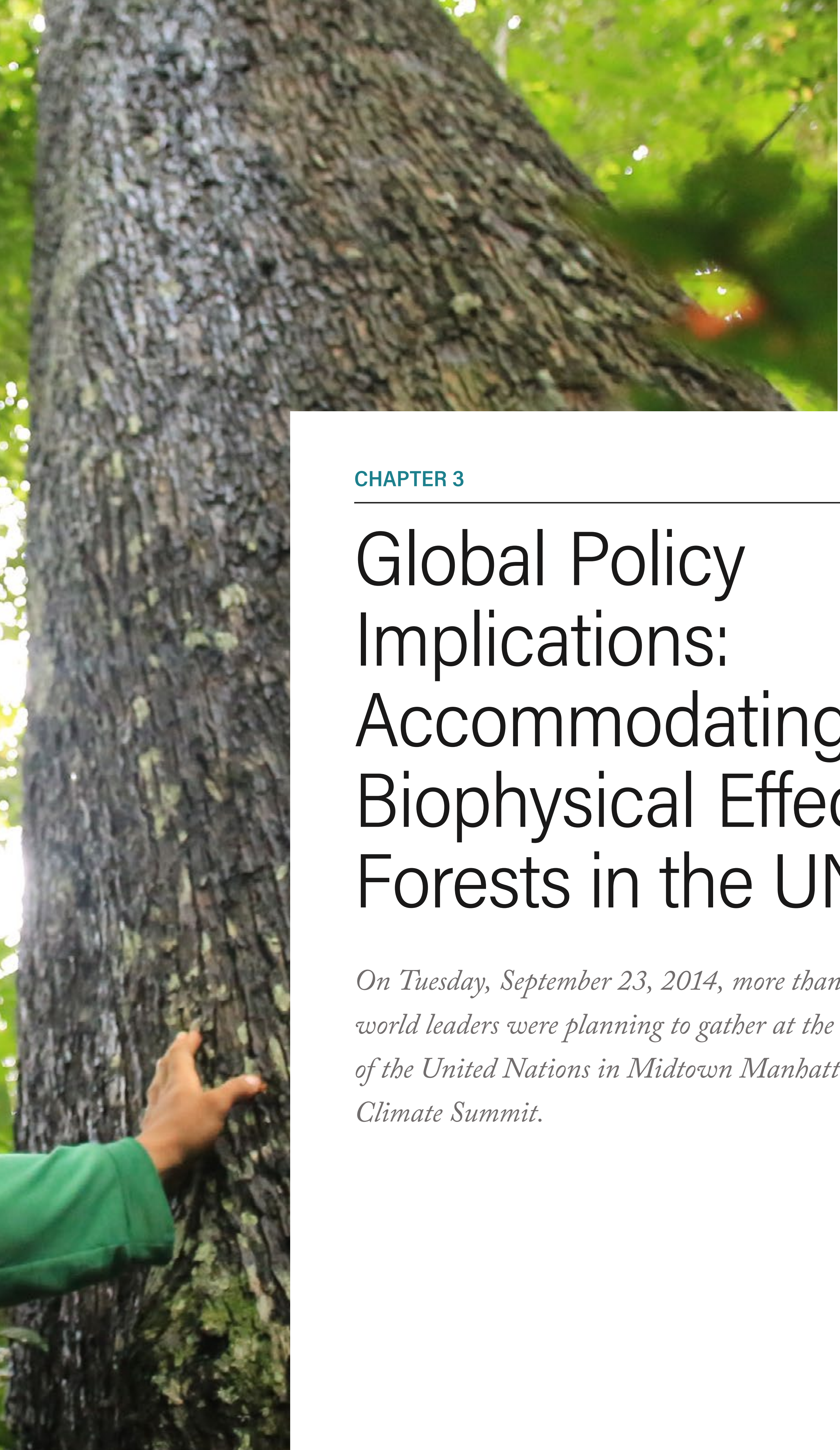
Models have explored scenarios ranging from continued extensive forest cover loss in the tropics and modest reforestation elsewhere (RCP 8.5, a representative concentration pathway with high baseline emissions) to massive-scale global afforestation (Arora and Montenegro 2011). The results of these models are generally consistent with the results presented above: at the global scale, GHG effects tend to dominate, with local biophysical effects generally as expected by latitude (although amplified in some models) and global average biophysical effects ranging from modest cooling to modest warming.

CONCLUSIONS

In planning for the future of forests, in a way that fully recognizes their role as climate regulators, the closer study of biophysical processes results in several clear scientific conclusions of relevance to policymakers at various scales:

- At regional and global scales, carbon and other GHG processes tend to dominate; while at the local scale, biophysical effects can be very large and dominate.
- Through their biophysical processes, forests help moderate local and regional temperature extremes everywhere in the world, in particular bringing down temperature extremes during the hottest times of day—improving resilience to global warming from the tropics to the boreal regions.
- Forests reduce the risks of heat-induced drought due to their water recycling and deep roots, and mitigate the adverse effects of both increases in rainfall in some places and decreases in others that are expected with global warming.
- In the tropics, forests provide a net global biophysical cooling effect that amplifies their global GHG cooling to a globally significant degree—increasing their climate buffering role by as much as 50 percent.
- This amplification could provide an additional global cooling equivalent of about 1.4 $GtCO_2$ per year or more if recent estimates of tropical forest mitigation potential are achieved.
- Outside the tropics, at a latitude somewhere between 30° and 56° North, depending on background climate, forests shift from providing net biophysical cooling to net biophysical warming, which begins to dampen rather than amplify the GHG cooling benefits of forests.
- Except for the very far north, where biophysical warming likely exceeds GHG cooling, forests reliably contribute to global climate cooling around the globe.

This review of the science linking forests and climate through recycling of moisture and energy reveals a complex push-and-pull of multiple processes across multiple scales. It is easy to dismiss this complexity as suggesting that we cannot include consideration of these processes in climate policy and planning. But this is, pardon the pun, missing the forest for the trees: the result of this complexity is that healthy forests regulate local climate, and forest loss will amplify climate risks, increase extremes, and lead to a potential breakdown of forests' local and global climate regulation services. We must understand, as best we can, the scale and direction of forests' climate regulation services, and design policies that seek to maintain these services, whether the forests themselves are nearby or on the other side of the planet.



CHAPTER 3

Global Policy Implications: Accommodating Biophysical Effects of Forests in the UNFCCC

On Tuesday, September 23, 2014, more than 120 world leaders were planning to gather at the headquarters of the United Nations in Midtown Manhattan for a Climate Summit.

One year earlier, UN Secretary General (UNSG) Ban Ki-moon had announced plans to host this summit, slated as a critical step for raising ambition on the "Road to Paris." The summit was to be something new on the international climate policy calendar—convened by the UNSG, but not wholly "of" the UN: as much about nongovernment entities as governments, and insulated from the push, pull, and veto of states. There was a high bar set for getting "on stage," with organizers demanding significant announcements of action and ambition from government, business, and civil society alike.

The world's proponents for forests as a key component of global climate action responded to the UNSG's call to action with nearly a year of intense discussions, negotiations, and organizing.

Ultimately, this process led to the New York Declaration on Forests (NYDF), a public-private partnership of companies, governments, civil society, and Indigenous Peoples pledging to do their part to achieve 10 ambitious global goals: halving forest loss by 2020 and ending it by 2030; meeting the private sector goal of getting deforestation out of agricultural commodities by 2020; restoring 150 million hectares of forests and degraded lands by 2020 and another 200 million by 2030; and more.

Throughout the spring and summer, and as the summit drew closer, Action Plans by countries, states, Indigenous Peoples, companies, multistakeholder groups, and civil society began to roll in, as "Forest World" competed for the summit's spotlight in a race to the top. Forest World was prepped, ready, and buzzing with positive energy, ready to do more than just announce ambitious goals. The NYDF was envisioned as a major marker to help hold signatories accountable for action and outcomes for years to come.

Then on the Friday before the summit, an opinion piece appeared in the New York Times *with a headline contrary to conventional wisdom and scientific consensus: "To Save the Planet, Don't Plant Trees" (Unger 2014b). Dr. Nadine Unger, an assistant professor of atmospheric chemistry at Yale, penned the op-ed (though not the headline) to draw attention to a risk she saw from her research: that forests might not have as much (or even any) net cooling effect on the climate as previously thought, due to biophysical and biogeochemical interactions between forests and the atmosphere. Just a few weeks prior, she had published a paper in the journal* Nature Climate Change, *which estimated the historical climate cooling impact of lost forest-derived BVOC emissions, added that cooling to the estimated albedo cooling effects, and compared them in sum to the warming impact of forest* CO_2 *emissions (Unger 2014a).*

Forest World responded in force, disputing the op-ed's headline and conclusions, concerned that more than a year of building toward this moment to elevate forests as a climate solution was under threat. A weekend of frantic emails, research, and organizing produced multiple rebuttals, some signed by the world's leading forest scientists. The blowback was not easy for Dr. Unger either.

In the end, the op-ed did little to derail the forest-related activities at the Climate Summit. The NYDF was launched successfully and remains an organizing platform and accountability tool through annual progress assessments, and endorsement of its overarching goal was broadened in the 2021 Glasgow Leaders Declaration on Forests and Land Use (Forest Declaration Platform 2021). The scientific research supporting a critical role for forests (and other natural climate solutions) in stabilizing the climate also continues to grow and strengthen.

This opening story is based on actual events in which one of the authors (Michael Wolosin) was a participant, and draws on Nepstad 2014, Griscom 2014, Griscom et al. 2017, Climate Advisers 2014, Popkin 2019, Pearce 2021, Forest Declaration Platform 2021, Project Drawdown 2021, and Falk et al. 2019.

The episode of the *New York Times* op-ed described above illuminates interactions between new and developing scientific understanding and the global agenda-setting and policymaking process, and the messiness that can entail. Dr. Unger was working on some important ideas at the forest-climate nexus: that the non-carbon interactions between forests and the atmosphere are significant for the climate; that the various biogeochemical and biophysical impacts of forest loss do not all result in global warming; that these processes and their net balance are worthy of additional study; and ultimately, that if we don't take these biophysical interactions into account, international climate policymakers risk making significant and potentially disastrous mistakes.

Since 2014, scientific understanding of biophysical and biogeochemical forest-atmosphere interactions has advanced further. The recently released report by Lawrence et al. (2022) shows that large-scale patterns of forests' *global* climate impacts—largely determined by whether and to what extent albedo, evapotranspiration, BVOCs, and other non-GHG effects amplify or cancel out greenhouse warming from CO_2—are well-enough understood to incorporate their effects into global policymaking. We must face head-on the inconvenient truth that there are places in the world where planting trees may not in fact achieve *global* warming mitigation, while in other places forests are achieving even more than we thought, and what this means for international climate policy—including how to balance attention to global effects with the fact that forests everywhere provide *local* climate stabilization benefits, and to ensure that global climate policy approaches sufficiently address the equity implications of the loss of forests' local climate stabilization benefits.

This chapter sets out to start such an assessment, focused primarily on the foremost international venue that seeks to address anthropogenic climate change: the United Nations Framework Convention on Climate Change (UNFCCC).

We begin with a brief summary of the emerging science on biophysical forest-climate effects that are relevant to international policy. Next, we explore implications of scale complexity, including the difference between physical scale and policy scale, and propose a set of legitimate (and specifically) *global* policy interests in such effects. Subsequently we narrow our focus to the UNFCCC, and to its associated processes, as appropriate. We take brief and optional detours into the history of forests in the UNFCCC and the critical role of the IPCC at the science/policy interface, before turning to an analysis of gaps and opportunities within the UNFCCC legal and institutional framework and its associated processes.

Within this context, we identify potential opportunities to stretch the boundaries of the existing UNFCCC mitigation framework to consider biophysical forest-climate processes, in particular where they have clear effects on global average temperatures. We also examine the opportunities offered by the existing adaptation framework for addressing international climate policy interests in more local physical-scale climate processes. Finally, we summarize the analysis and draw out key takeaway messages.

SCIENCE OVERVIEW: BIOPHYSICAL PATHWAYS RELEVANT TO INTERNATIONAL POLICY

As already presented in Chapter 2, forests interact with the climate in multiple ways at scales from local to global. This section briefly summarizes the most relevant forest-climate interactions for international policymakers.

The most significant forest-climate interaction at the global scale is forests' role in storing carbon or releasing it as CO_2. Forestry and other land use (including deforestation and reforestation) account for about 11 percent of total human-caused CO_2 emissions (about 5.5 billion tons per year). This deceptively small number is the result of a subtraction: about 16 billion tons of CO_2 emissions from deforestation, forest degradation, and ecosystem losses in some places, minus about 10.5 billion tons of CO_2 sequestrations in other places—obscuring the fact that increased sequestration in some places and reduced emissions in other places can provide mitigation at the same time (see Chapter 2).

In addition to these impacts via the carbon cycle, four types of non-greenhouse forest-climate processes—biophysical mechanisms that cycle energy and moisture—have large combined climate effects at the local and regional scales, while also amplifying or moderating forests' contributions to the greenhouse effect on global climate. First is the amount a surface reflects sunlight (its albedo). Forest canopies are usually darker (lower albedo) than the surfaces that replace them or are exposed when trees are removed—especially in colder climates where snow is a more frequent alternative. Their darker surface absorbs more sunlight than if no forests were there—a warming effect.

Second is evapotranspiration, liquid water gaining energy and turning into water vapor either from surfaces (evaporation) or out of leaves (transpiration). Forests—especially those in warmer and wetter areas—are incredibly efficient at evapotranspiration, which transfers heat and water from land into the atmosphere, cooling the air and surface and increasing humidity and downwind rainfall both near and far.

Third are the ways forests interact with passing wind through their surface roughness: creating turbulence that slows near-surface winds and cools the land as it lifts heat from low-albedo leaves and moisture from evapotranspiration high into the atmosphere and slows otherwise-drying winds.

And last, a complex but increasingly well-studied group of secondary effects include emissions of aerosol particles such as pollen and fungal spores and quickly vaporizing chemicals such as isoprene and terpenes. These aerosols absorb and reflect energy, affect cloud formation, and chemically alter other atmospheric components such as ozone. The net warming vs. cooling of these secondary effects in various places and on average is less certain than other processes.

> Tropical forests provide additional global climate benefits through biophysical effects above and beyond their global carbon benefits.

The combined effect of forests and forest cover change on the climate through all of these biophysical processes depends on the spatial scale of interest and on the location of the forests themselves—largely their latitude. While glossing over significant and important details (see Chapter 2), several clear patterns in temperature effects emerge:

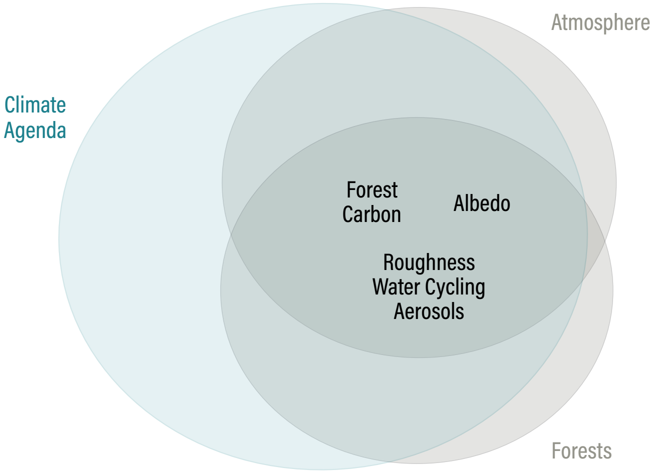
- ***All* forests provide *local* climate benefits through biophysical processes.** Deforestation exacerbates temperature and moisture extremes, while reforestation buffers them.
- ***Tropical* forests provide additional *global* climate benefits through biophysical effects above and beyond their global carbon benefits.** In the tropics, there is a net biophysical warming from forest loss, which *amplifies* the global warming from deforestation's carbon emissions.
- **Tropical forests' biophysical global cooling benefits are large enough to be *globally significant*, amplifying the CO_2 sequestration-based temperature benefits of tropical forests by about 50 percent.**
- ***Midlatitude* forests provide *net global* climate benefits from biophysical effects and GHGs together, but less than their carbon-only effects**. Somewhere between 20° and 30° North, the net biophysical effect of deforestation switches from warming to cooling but remains smaller than the greenhouse warming from CO_2 emissions.
- **In *boreal* regions, forests' biophysical warming exceeds their greenhouse cooling, for *net global warming*.** Above about 40° to 50° North, the net global cooling signal of deforestation from biophysical processes exceeds the greenhouse warming signal from CO_2 emissions, even though boreal forests do provide important local climate regulation services.

FROM SCIENCE TO GLOBAL POLICY: PHYSICAL SCALE, POLICY SCALE, AND SCOPE

To take the step from summarizing science to assessing its implications for policy, it is important to make a distinction between the geographic scale of a physical process (its "physical scale"), and the geographic scale of a policy venue or process within which that forest/climate interaction may be relevant (the "policy scale" divided above in Figure 1.1 into local/national, regional, and global contexts). The interests of global policymakers in a given process will depend in part—but not entirely—on the physical scale of its effects.

Forest change drives changes in both the atmosphere and on land that affect the primary indicator of global warming: average temperatures on the surface of the earth (see Box 3.3 for discussion of indicators). The global land surface air temperature has risen by about 1.5°C from the preindustrial period to today, while the global mean surface temperature (including the sea surface temperature) has risen more slowly (just below 1°C over the same period) (Jia et al. 2019, 133).

FIGURE 3.1 | The Climate Agenda and Forest-Atmosphere Physical Processes



Source: Authors.

Forest-climate interactions at *any* physical scale that affect these global average temperatures are clearly of interest to international policymakers.

Forest-climate interactions can also drive changes in regional-scale climate patterns. For example, modeling experiments that add or remove large amounts of forest show changes in multiple atmospheric circulation patterns around the world—up to and including shifts in planetary wave patterns that determine regional climates (Snyder 2010; Mahmood et al. 2014). These regional-to-global physical-scale forest-climate interactions are relevant to international policy as well, apart from their effects on global average temperature.

What about those forest-climate processes whose most significant impacts are at the local scale, such as rising temperature and increased variability and extremes of temperature and rainfall? Of course, local temperature increases in enough places at once not counterbalanced by temperature decreases elsewhere can drive an increasing global average.

However, considering only those processes that affect global temperature is too narrow a view of global climate policy. **Anthropogenic climate change is not just about global averages.** The patterns of climate disruption vary across local to global spatial scales, and at hourly to decadal temporal scales, with the extremes—in cities, in coastal areas, in the already hot tropics—having an outsized impact on those people least responsible for the changes and least equipped to adapt.

How does this scale complexity play out in global climate policy, and where are there gaps? One might define the international climate agenda broadly as "a common and shared interest in avoiding dangerous anthropogenic interference in the climate, and equitably addressing the impacts of such interference." What does it mean to say, "the climate"? For the sake of discussion, we define it here broadly to mean the climate anywhere (i.e., we don't say "global climate" here intentionally). The global scale of this climate policy agenda does not preclude interest in local physical-scale forest-climate processes. Thus, a global climate agenda broadly defined could clearly be concerned with all of the forest-atmosphere physical interactions (represented by the overlap between the two gray circles on the right) discussed in this report (Figure 3.1).

In what specific ways is the global climate agenda implicated by the biophysical effects of forest land-use change?

- To the extent that such biophysical processes affect the amount of the sun's energy that stays in the atmosphere and/or average surface temperature, the climate-related results of human-driven forest cover change are clearly human interference in the climate. They are of legitimate interest to international climate policymakers for all of the same reasons as GHG emissions are.
- The existing international climate policy framework provides incentives to countries to take actions in their forest and land sectors to reduce GHG emissions and increase sequestrations. If unaccounted for, the effects of biophysical processes that amplify or dampen global GHG climate effects may distort incentives, resulting in policy incoherence and potentially perverse—or at least suboptimal—outcomes.

In addition to those impacts on the global climate, the impacts of interactions between forests and the atmosphere at subglobal scales worldwide have global policy implications.

- Biophysical processes affect global climate patterns above and beyond just temperature, for example, through regional moisture transfer and impacts on global circulation patterns. Addressing regional and cross-border climate impacts is clearly a collective action problem with potential implications for peace and security, trade, human rights, environment, and more—and thus also clearly in the scope of international climate policy writ large.[7]
- Biophysical processes that have primarily local to national-scale effects are also in the legitimate interest of international climate policymakers. Local temperature and rainfall changes from forest change, including increased variability and exacerbated extremes (see Chapter 5), are layered on top of climate changes caused by globally mixed GHGs, with nonlinear impacts and thresholds that put people and nature at significant risk. International climate policymakers will fail to address the health, well-being, and equity impacts of climate change if they only "count" one kind of human-caused climate change as relevant.

The next section seeks to identify potential opportunities for closing these gaps in global policy on climate change in the context of the UNFCCC, where forests' climate interactions have historically been addressed (see Box 3.1).[8]

BOX 3.1 | History of Forests in the UNFCCC

Concern about human-caused climate change was elevated to a global conversation as early as 1979 at the First World Climate Conference, a scientific gathering sponsored by the World Meteorological Organization. This led to the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, with a mandate to provide scientific information to governments in order to develop climate policies. The global consequences of climate change and the necessity for international cooperation to address it were laid bare in the IPCC's First Assessment Report of 1990, which fed into the international negotiations leading up to the 1992 adoption of the UN Framework Convention on Climate Change (UNFCCC) at the Earth Summit in Rio.[a]

Reports from the scientific community designed to inform international climate policy have included forests from the start—and not just their role in the carbon cycle and GHG emissions. Perhaps surprisingly, the First Assessment Report (FAR) by the IPCC includes a discussion of the climate impact of albedo changes arising from deforestation even before fossil fuels or deforestation are discussed in the context of carbon emissions.[b] Nevertheless, forests' carbon emissions were the primary mechanism of focus with respect to their climate effects. The FAR estimated human-caused CO_2 emissions of "5.7±0.5 Gt C (in 1987) due to fossil fuel burning, plus 0.6±2.5 Gt C (in 1980) due to deforestation."

Forests were also included in scientific assessments of potential policy responses from this early period. For example, the Response Strategies Report of the 1990 FAR recommended that all countries take steps to adopt clear objectives for forest conservation and amend national policies to minimize forest loss associated with development.[c]

The policy response to forests' climate impacts in the context of the UNFCCC was slower to take root than in the IPCC's assessments, however. This was in part due to significant uncertainty in forest emissions estimates—although some direct observers have suggested this issue was largely used as a stand-in for concern that forest mitigation would be used to delay action by the fossil sector. It was also related to concerns about equity issues between developed and developing countries.[d] Most deforestation emissions during the era of the UNFCCC have been—and continue to be—from tropical developing countries (even though this wasn't the case in the 19th century and the first half of the 20th century), while the bulk of fossil emissions were coming from developed countries.[e] This fact, in the context of the UNFCCC principle of "common but differentiated responsibilities and respective capabilities," resulted in greater urgency being placed on the fossil emissions agenda.

Although the Kyoto Protocol required developed countries to account for forest-related emissions, and afforestation and reforestation in developing countries were included in the Clean Development Mechanism, reduced deforestation was excluded.[f] At the 11th Conference of the Parties to the UNFCCC (COP11) in 2005, Papua New Guinea and Costa Rica sought to address this exclusion by requesting a new and separate agenda item on "reducing emissions from deforestation in developing countries," a concept that has evolved through a series of agreements and decisions into "reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries" (commonly known as REDD+) as outlined in the Warsaw Framework and Article 5 of the Paris Agreement.

Sources: a. UNFCCC 2021; b. World Meteorological Organization 1991, xv; c. World Meteorological Organization 1991, 78; d. Seymour and Busch 2016; e. Houghton 2013; f. United Nations Treaty Collection 1997.

THE UNFCCC: FORMAL AND INFORMAL SCOPE

The UNFCCC writ large, including its associated conferences, meetings, and subsidiary processes, is without doubt the primary international venue for global policy on climate change. As we seek to identify gaps and opportunities within the UNFCCC context, it is critical to recognize that the formal legal scope of the Convention and its agreements is not the same as the scope for potential awareness-raising within and adjacent to UNFCCC *venues*. The UNFCCC Conference of the Parties (COP) is the largest annual gathering of global climate policymakers and provides both formal and informal mechanisms for raising issues and creating room for additional research and policy considerations. Some of these efforts might eventually make their way into the formal agendas of the UNFCCC bodies (be they procedures, processes, or negotiations), while others might progress outside the UNFCCC (see, e.g., Box 3.2).

It is nevertheless important to consider the formal scope of the Convention and its agreements per se. And in this sense, the UNFCCC is more limited in scope than the expansive view the climate agenda, as depicted in Figure 3.1, represents. The wording of the Convention provides a legal foundation for the work of the UNFCCC and sets out its objective as achieving "stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992). This starting point for the UNFCCC set countries down a path that has largely ignored biophysical influences on the climate system.

However, there *is* room within the Convention text for work beyond "stabilization of GHGs." For example, Article 3.1 sets forth the principle that "the Parties should protect the climate system for the benefit of present and future generations of humankind," where "climate system" is explicitly defined as "the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions" and obviously includes all the forest-climate processes discussed above. Article 3.3 sets out the principle that "Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change," while "climate change" is defined as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere." In this definition, one might find all the biogeochemical forest-climate processes (carbon emissions and sequestrations, methane emissions) and some of the biophysical processes (evapotranspiration, BVOCs, even nongaseous aerosols, etc.) that influence the "composition of the atmosphere"—but probably not albedo or surface roughness effects.

BOX 3.2 | A Research, Science, and Policy Nexus: The IPCC

The Intergovernmental Panel on Climate Change (IPCC) and its working groups and special reports remain an important venue for examining the physical science basis of forest-climate interactions, the effects of these interactions, and the potential for forests as a climate mitigation opportunity. Unlike the UNFCCC, the mandate of the IPCC is not limited to GHGs; as such, it has a long history of addressing biophysical forest-climate interactions within its scope. The 2019 *Special Report on Climate Change and Land* (SRCCL), published as part of the Sixth Assessment Report (AR6) cycle, included extensive discussion and synthesis of biophysical interactions between the land and atmosphere. The AR6 Working Group Reports and Synthesis Report also address these processes in various ways.

Any successful global framework for addressing biophysical forest-climate effects will require an effective science-policy interface that draws the scientific community into the process of additional research, assessment, and technical guidance on quantification. For example, as the primary venue for providing technical guidance regarding GHG inventories, including for the land-use sector (e.g., the Good Practice Guidance for LULUCF), the IPCC could play a key role in assessing whether and how biophysical global surface temperature effects of forests can be inventoried and accounted for. The IPCC could research how and whether the LULUCF Good Practice Guidance could be updated to provide appropriate methodologies for estimating net global temperature change effects of forests, and of forest cover change, from existing forest and land-use inventory data).[a]

Source: a. IPCC 2003.

In seeking to understand the structure and development of the UNFCCC, it is useful to distinguish between three responses to "anthropogenic interference with the climate system," which have dominated the discourse: emissions abatement,[9] carbon dioxide removal (CDR), and adaptation. (The following discussion leans on the analysis by Jesse Reynolds in *The Governance of Solar Geoengineering* [2019], which examines questions surrounding *solar radiation management* as a means of addressing climate change, another topic relevant to international climate policy but largely absent from the UNFCCC process. See Box 3.3.)

CDR options, ranging from tree-planting at the nature-based end of the spectrum, to CO_2 air-capture at the technological/industrial end, are clearly within the scope of UNFCCC discourse, and have received increased attention over the years. As we have failed to sufficiently avoid GHG emissions and/or recapture those emissions, a third response—adapting to a changed climate—has shifted from being seen as taboo and "defeatist" to being central to the international climate policy discourse. Recent agreements follow a "mitigation/adaptation" structural dichotomy, each domain with specific commitments, reporting requirements, and separation of responsibilities between developed and developing parties. And while the discourse has continued to evolve—for example with an increased recent focus on "resilience" rather than "adaptation" per se, and with "transition pathways" or "decarbonization strategies" taking the rhetorical place of "mitigation"—the structural dichotomy remains largely in place.

Some provisions recognize this dichotomy as somewhat artificial. For example, whether an action by a party is best considered as "adaptation" or "mitigation"—or even combined "adaptation/mitigation"—has been left open to interpretation in the context of climate finance reporting. This is particularly relevant for forests: maintaining and enhancing forests are rare global emissions abatement strategies that also contribute to local adaptation. Regardless, the dichotomy between mitigation and adaptation is well established in UNFCCC discourse and decisions—and continues to drive the politics of topics such as climate finance, where a choice to account for forest finance as adaptation would have significant consequences.

On the mitigation side of this split, the UNFCCC discourse and decisions have also been shaped in part by limiting the scope of mitigation—so far—to include only emissions abatement and CDR. However, in the past decade or so the UNFCCC has taken steps toward expanding the objectives of the Convention in ways that could support expanding this scope. The signatories of the 2009 Copenhagen Accord (Decision 2/CP.15) agreed for the first time to a target of "below 2° Celsius" rise in global temperature (UNFCCC 2009). The 2015 Paris Agreement solidified this expansion of the UNFCCC objectives and strengthened it further to "Holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC 2015, Art. 2.1a).

This change is fundamental: whereas the Convention's original objective of "stabilization of GHG concentrations" pushed the entire evolution of the UNFCCC toward a limited view of mitigation, it could be argued that explicit temperature targets included in the Paris Agreement bring within the UNFCCC's formal *legal* scope any and all actions that can help achieve them. Such actions could include widespread forest management for the purpose of maintaining and expanding forests' biophysical cooling effects, as contributions to global average temperature targets

> Whereas the UNFCCC's original objective of "stabilization of GHG concentrations" pushed its evolution toward a limited view of mitigation, . . . explicit temperature targets . . . in the Paris Agreement bring other actions into the UNFCCC's formal legal scope.

and part of climate transition pathways. Box 3.3 examines the implications of several different indicators that are used to measure climate progress.

However—and this is a significant "however"—the UNFCCC as a global climate policy venue, and the Paris Agreement as its most recent articulation, both speak to far more than just an ultimate climate objective, be it GHG stabilization or limited surface temperature increase. They also establish a specific and complex framework for how these objectives will be achieved: largely through mitigation of GHGs, but also through adaptation; supported by climate finance and technology transfer; monitored through transparency and reporting, and so on.

In short, we face a fundamental mismatch between the Convention's objective and the framework established to achieve that objective. The paradigm of what climate change *IS* has already shifted within the UNFCCC beyond just GHG emissions (climate change as a process that happens "up there" in the atmosphere) to now include global temperatures ("down here," where people experience it). However, the organizing principles of the UNFCCC, including those embedded in the Convention as well as those that have evolved over time as the scope of discourse and various agreements, do not yet reflect this fundamental change.

BOX 3.3 | Climate Change Indicators: PPM, $GtCO_2$, degrees C

Numbers are one of the critical interfaces between science and policy, and the numbers that policymakers focus on can have a large effect on what they try to manage and the lessons they extract from data and science. International climate policymakers—and activists—have long focused on a set of indicators that tend to narrow the scope of their actions. In line with the 1992 UN Framework Convention's objective of "stabilization of GHG concentrations," policymakers sought, and scientists provided, estimates of such concentrations that might prevent "dangerous anthropogenic interference with the climate system"—around 350 or 400 parts per million (ppm) CO_2 in the atmosphere.[a]

In some ways, atmospheric GHG concentration is a better measure of our global warming impact than anthropogenic GHG emissions, as the oceans and biosphere absorb a large portion of our emissions, and because concentration integrates emissions over time to describe the actual state of GHGs in the atmosphere. In other ways, though, it fails: the GHG concentration tells us a lot about radiative forcing—the imbalance between incoming and outgoing radiation that drives the greenhouse effect—but it tells us less about the ultimate distribution of extra energy between different parts of the earth-ocean-atmosphere system. Some of the drivers of climate change alter these distributions, including biophysical effects of forest and land cover change, which may, for example, warm the earth's surface while cooling parts of the atmosphere. For these types of effects, surface temperature changes—such as the 1.5° or well below 2°C goals that are now such critical markers—are better at representing the warming that people and ecosystems actually feel at the surface where we live.

But even global average temperature targets fail to capture climate changes that impact people's lived experiences: changes in extreme temperatures rather than averages, changes in frequency and duration of droughts, or severity of heavy rainfall events or hurricanes, or shifts in the timing of seasons, and more. But there are no simple indicators to summarize these "global weirding" impacts on the distribution of temperature, water, and energy across space and time into a single number across the entire world.

While we can estimate the relative impacts of forest-related biophysical effects at the global scale using the basic metrics of temperature change and CO_2-equivalents,[b] some of the biggest effects are scale-dependent—about extremes and distributions, not averages. Without simple indicators for these "other" climate changes, it becomes a fait accompli that they are neglected by policy.

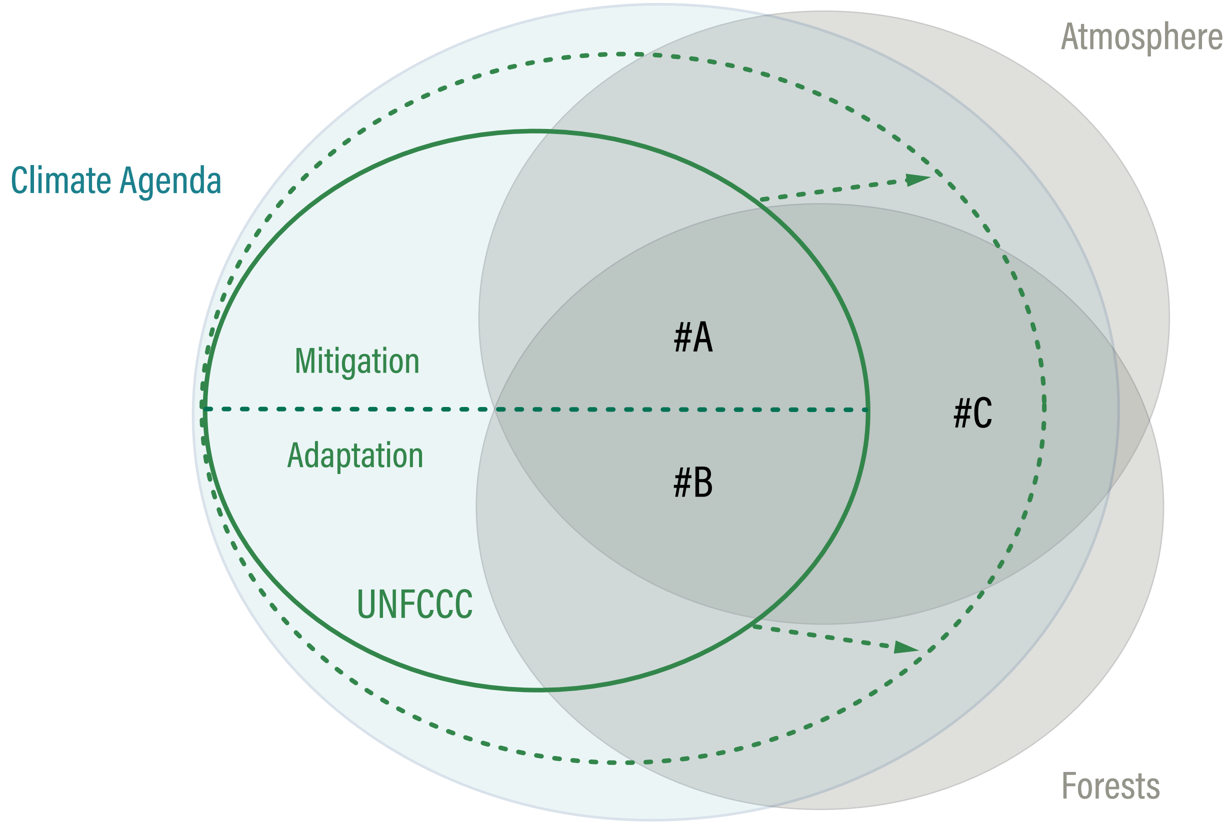
Sources: a. UNFCCC 1992. b. Windisch et al. 2021.

This observation need not lead to the conclusion that addressing biophysical global climate impacts of forest cover change could not or should not have a role in meeting the UNFCCC's objectives and the Paris targets. But it does suggest that incorporating the implications of those impacts *through the formal negotiations* would be a lengthy process. As noted above, though, the UNFCCC is more than just the formal negotiations. If there is any policy venue in the world where there is a level of attention focused on climate by policymakers, leaders, businesses, nongovernmental organizations (NGOs), and media sufficient to begin shifting the paradigm of what climate change is and what policymakers should address, then the UNFCCC is it. Whether or not biophysical processes are ultimately addressed within the formal UNFCCC framework, it nevertheless is important to examine potential docking points where the concerns of omission rise to enough significance to begin influencing the discourse and eventually policy responses.

Figure 3.2 presents a model for overlaying this discussion of the UNFCCC's policy scope onto the physical atmosphere/forest interactions as represented by the Venn diagram above (Figure 3.1). The oval represented by the solid green line represents the formal UNFCCC scope, including the mitigation-adaptation dichotomy that splits the UNFCCC and frames so much of its existing workstreams and process (the dashed horizontal line). A dashed green oval represents the potential of UNFCCC processes to take a broader view, as the new temperature goals might suggest is necessary.

Three areas of the Venn diagram of Figure 3.2 are of particular interest.

FIGURE 3.2 | The Climate Agenda, UNFCCC, and Forest-Atmosphere Processes



Note: UNFCCC = United Nations Framework Convention on Climate Change.

Source: Authors.

Area #A: Forest carbon emissions into the atmosphere—such as CO_2 from burning trees to convert forest to agriculture—fall firmly within the existing scope of the UNFCCC as anthropogenic GHG emissions. Enhanced forest sequestrations and other nature-based CDR also fall firmly within the formal UNFCCC scope; both would be considered climate mitigation by any definition. Forestry and other land use (FOLU) reporting requirements and accounting rules are well established; REDD+ provisions are well developed as the international policy approach to provide incentives for protecting and enhancing forest carbon in developing countries specifically; and the bottom-up country goal-setting in Nationally Determined Contributions (NDCs) provides a context for country actions in the forest sector including both mitigation and adaptation.

Area #B: Within the existing UNFCCC context, actions beyond GHG mitigation that are intended to enhance the resilience of a community to the impacts of a changing climate would be considered adaptation. We examine briefly whether policies directed toward addressing the local to subglobal climate effects of forest/atmosphere processes (such as evapotranspiration, surface roughness, and the local heating/cooling effects of albedo) could fall within the scope of the UNFCCC adaptation framework.

Area #C: Because some forest-climate processes that have a significant effect on the global surface temperature—such as albedo, evapotranspiration, and BVOC emissions (see Figure 1.1)—are not related to GHGs, they fall outside the current scope of UNFCCC frameworks and discourse, but within a potentially expanded scope that global temperature goals suggest. Note that *geoengineering* through solar radiation management (e.g., injecting aerosols into the atmosphere to reflect incoming sunlight) is a nonforest analogue that falls in this gap (see Box 3.3). These biophysical processes also affect global climate circulation patterns, and other large-scale climate phenomena, beyond their effect on surface temperatures. The collective action problem of avoiding these types of biophysical forest-mediated global climate disruptions beyond temperature is largely outside the current structure of the UNFCCC discourse, even if it were to evolve toward managing and mitigating surface temperatures rather than simply GHG emissions.

Biophysical forest-climate interactions also have significant effects on temperature and rainfall extremes and variability, and on the spatial distributions of energy and water beyond their averages and extremes in one place. Some of the effects of these processes may be partly addressed (or even better addressed) at subglobal policy scales. For example, we investigate opportunities to address terrestrial moisture recycling in regional policy arenas in Chapter 4, and local temperature effects of forest change on human health and agriculture effects at national and local scales in Chapter 5. Other effects of biophysical forest-climate interactions may fit comfortably within the existing adaptation framework (e.g., perhaps Area #B is sufficient as is to address the legitimate international climate policy interests in impacts at below-national scales). In the following sections, we explore a few potential options for shrinking the gap represented by Area #C—noting that our intent is not to provide an exhaustive analysis of all the potential options, but rather to provide examples. A few additional options are mentioned briefly in the chapter's conclusions.

OPPORTUNITY: EXPANDING NDC MITIGATION BEYOND GHGS

At the very heart of the Paris Agreement is the bottom-up Article 3 commitment by countries to "undertake and communicate ambitious efforts" in the form of "nationally determined contributions to the global response to climate change." To a large degree, the rest of the Paris Agreement is simply an elaboration of requirements for setting, communicating progress on, and strengthening these NDCs over time. While NDCs include both adaptation and mitigation components, we focus here on mitigation and discuss adaptation below.

The scope of mitigation commitments that countries may voluntarily put forward within their NDCs is not strictly limited to GHGs. For example, Mexico's inclusion of a commitment to reduce short-lived climate pollutants ("SLCPs"—pollutants such as near-surface ozone and *black carbon* particulates) in its NDC provides an interesting policy analogue described in Box 3.4.

BOX 3.4 | Policy Analogue: Black Carbon

Black carbon is a particulate form of carbon that is released from the incomplete combustion of carbon-based fuels. It is an important contributor to climate change as a short-lived climate pollutant (SLCP) with a warming impact ~460–1,500 times that of carbon dioxide (CO_2).[a] Black carbon provides an interesting policy analogue for the biophysical and biogeochemical effects of forests on climate. In fact, it is an additional forest-climate interaction itself, as black carbon is emitted by forest fires as well as from grassland fires, biomass burning for energy, and fossil energy. In all of these cases, there is a mix of local to global effects, including on global temperature, rainfall, and human health. And all are largely outside the scope of the UNFCCC framework.

This gap has not prevented a few countries from seeking to address black carbon in the context of UNFCCC mitigation. The earliest example is Mexico, which included black carbon in its 2015 intended NDC.[b] It committed to a 25 percent reduction of "its Greenhouse Gases and Short Lived Climate Pollutants emissions (below BAU [business as usual])," explicitly stating that "This commitment implies a reduction of 22 percent of GHG and a reduction of 51 percent of Black Carbon." A footnote provides additional information that the commitment is consistent with national law to "prioritize cost-effective mitigation actions with social benefits such as the improvement of public health," suggesting that Mexico is prioritizing the reduction of black carbon due to the health cobenefits this affords. Chile followed Mexico's lead in its NDC update of April 2020, expanding discussion of the country's efforts to reduce SLCPs and including a new commitment to reduce black carbon emissions by at least 25 percent by 2030.[c]

Sources: a. Raga et al. 2018; b. GOM 2015; c. GOC 2020.

There may be an opportunity for one or more tropical forest countries to explore a similar approach vis-à-vis the global average temperature impacts of their forests through biophysical processes. A country could include the expected global cooling impacts through biophysical effects from reduced deforestation or planned reforestation within their NDC climate mitigation commitment. This would not be simple: myriad technical and political challenges would need to be overcome. But because the current global climate policy regime only considers global GHG impacts (Figure 3.2, Area #A) and does not account for the additional global climate benefits of tropical forests through biophysical effects (Figure 3.2, Area #C), international climate policy is undervaluing tropical forests and the actions that tropical countries can take to slow and reverse forest loss. Tropical countries could seek to address this undervaluation directly by quantifying the additional benefit and seeking international recognition of its value through the NDC process, recognizing that the limited capacity of some forest countries may make this difficult without significant additional support.

On the flip side, international climate policy may also be *overvaluing* temperate and boreal forests from the radiative forcing perspective, by considering only GHG impacts and not biophysical effects. In the midlatitudes, biophysical warming of increased forest cover offsets some of the greenhouse cooling effect of more forests. This suggests that countries such as the United States with expanding forests may be having a larger radiative forcing impact on the globe than their GHG inventories indicate, as these inventories subtract forest carbon sequestrations one-for-one from other carbon sources.[10]

OPPORTUNITY: REDD+

A second and partly overlapping set of abatement-related opportunities may be available through the UNFCCC Framework for REDD+. REDD+ is included by reference in Paris Agreement, Article 5.1, which incorporates prior guidance and decisions and specifically "[reaffirms] the importance of incentivizing, as appropriate, non-carbon benefits" (UNFCCC 2015).[11] Similar to other abatement provisions, it is clear from both the written guidelines and the practice and history of REDD+ that it is designed to support and credit carbon and GHG abatement only—not other pathways to mitigating climate changes. While an exhaustive assessment of potential "docking points" for biophysical climate impacts of forest change within the full REDD+ framework is outside the scope of this report, we do identify opportunities that could be further explored. (The analysis that follows was greatly facilitated by "Mapping REDD+: A Visual Guide to UNFCCC Decisions," WWF 2017.)

The REDD+ provisions have built in two key concepts (also present elsewhere in the UNFCCC) that may allow space for consideration of biophysical forest-climate processes: progression over time in the quality and coverage of data and commitments, and recognition of development objectives beyond climate mitigation. The first principle is evident, for example, in the "stepwise approach" to Forest Reference Emissions Levels (FRELs), which enables parties to incorporate "better data, improved methodologies, and, where appropriate, additional pools" (Decision 12/CP.17 Par 12) over time. The second principle—that broader development objectives frame how parties plan and pursue mitigation and adaptation—is also explicit in the REDD+ provisions. For example, "the importance of incentivizing non-carbon benefits for the long-term sustainability of the implementation of REDD+ activities" is explicitly recognized, and those benefits can be documented and supported by REDD+ finance (Decision 18/CP.21 Par 4).

> Two key concepts within REDD+ (stepwise improvement and non-carbon benefits) provide openings for countries to begin addressing biophysical climate benefits.

These two key concepts (stepwise improvement and non-carbon benefits) and the pathways for their implementation within REDD+ provide openings for countries to begin a process of financing, quantifying, reporting on, and being rewarded for biophysical climate benefits as part of their UNFCCC REDD+ efforts. Where evidence shows that the total *global* cooling benefit of REDD+ (including via biophysical pathways) exceeds the carbon-only benefits—which will clearly be the case in the tropics—countries should consider bringing this analysis forward as a proposed stepwise improvement in their accounting for mitigation achievements with respect to a FREL under the REDD+ mechanism.

Countries could also consider including the net global cooling benefit of REDD+ beyond carbon in their offerings and price negotiations in carbon markets, including under Article 6. At the same time, buyers could be encouraged to

invest in (and recognized for investing in) those activities or related credits that generate additional global cooling benefits. If equitable benefit-sharing of REDD+ revenues is ensured, the appropriate valuation of those additional benefits could be especially important to Indigenous Peoples, who steward most of the world's remaining forests in their territories and are proven to be effective guardians of those forests (RRI 2018; Veit 2021; FAO and FILAC 2021).

Quantifying the additional global cooling benefits of forests in a way that could be subject to measurement, reporting, and verification protocols would pose a challenge, but at minimum, current crediting of tropical forest carbon should be qualitatively recognized as inherently conservative. These actions—pushing the boundaries of existing REDD+ practices, but well within the bounds of achieving its objectives—could help correct the current international climate regime's undervaluing of tropical forests' global cooling benefits.

In any case, countries should not hesitate to bring forward evidence of the biophysical climate stabilizing impacts of forests as part of their measurement and reporting of non-carbon benefits. Reporting such benefits alongside those of biodiversity, land rights, and poverty reduction, among others, would be noncontroversial, and could easily include the full range of biophysical forest-climate interactions summarized above.

LOCAL FOREST-CLIMATE EFFECTS AND THE ADAPTATION FRAMEWORK

The primary focus of this chapter thus far has been to assess gaps and opportunities in the international climate policy framework for addressing the global-scale effects of biophysical forest-climate interactions. However, one of the most important climate services provided by forests—one that applies almost everywhere, regardless of latitude or forest type—is their role in *local* climate regulation: moderating nearby temperature and moisture variability and extremes and mitigating the risks and damages these would otherwise impose on people and physical assets. The Paris Agreement's global goal on adaptation—to enhance adaptive capacity and resilience, and to reduce vulnerability, with a view to contributing to sustainable development—makes it clear that these local physical-scale climate processes are squarely within the scope of the international climate policy agenda. This is particularly true where they mitigate or exacerbate the risks faced by people and ecosystems as a result of being layered on top of GHG-based global warming.

There is a clear theoretical difference between taking action to *avoid* future changes in the local climate and associated risks therein (e.g., by changing land-use decisions regarding forest cover) and taking action to *reduce the* *future impacts* of climate shifts on people. In other words, the mitigation/adaptation dichotomy is real. However, in real-world policymaking contexts—encouraging and supporting planning and decision-making that enhance the resilience of communities to climate warming, extremes, and variability—this very real distinction in objectives not only breaks down, but often reveals synergies rather than trade-offs. The *mechanisms* for achieving these policy objectives are likely the same regardless of whose action is leading to the additional climate exposure and whether the mechanisms transferring climate risk are global or local. The UNFCCC framework itself recognizes that there is no bright line between "adapting to" inevitable shifts, vs. "mitigating" these shifts through some type of local or regional climate control policy, for example by allowing for combined adaptation and mitigation actions and credit for supporting such actions.

However, the adaptation/mitigation dichotomy *is* very real in terms of UNFCCC structure and many of its associated funding mechanisms. In the face of this dichotomy, there may be value in splitting consideration of biophysical forest-climate effects into global temperature effects, addressed by expanding the UNFCCC's mitigation framework in line with the above analysis, and more local effects—those centered on human resilience and vulnerability to a changing climate in specific places—which could be dealt with through the UNFCCC's adaptation framework, including through the adaptation-specific components of the NDC process and through National Adaptation Plans (NAPs).

This consideration is particularly pertinent with respect to the policy approaches and processes that are currently advancing to address adaptation within the UNFCCC. The adaptation framework is being developed with an understanding that international policy has a legitimate interest in local and within-nation implementation programs and thus must take consideration of the transboundary effects of national strategies (Magnan and Ribera 2016). In other words, the framework recognizes that adaptation actions and responses must cross multiple spatial and policy scales, and that international policy processes should legitimately engage in financing and supporting adaptation at all scales. Any successful attempt to address the biophysical climate effects of forests with an international climate policy perspective will need to similarly operate at and take into consideration multiple scales of decision-making and impact.

From a process standpoint, the adaptation framework has developed more slowly than the mitigation framework, and thus focuses in part on a learning approach and a model of bottom-up action combined with procedural rules regarding communication and reporting of actions and results rather than quantification and metrics. The bottom-up focus is also seen in the movement for locally led adaptation action, recognizing that resilience-building measures must be context-specific (Soanes et al. 2021). This bottom-up process supporting experimentation and learning will be equally necessary in addressing local forest effects on climate and will need to build on the traditional knowledge of Indigenous and local communities.

Overall, it is our assessment that the developing UNFCCC adaptation framework and dialogue provide sufficiently robust opportunities for consideration of local forest-climate interactions to merit further effort in this direction. The framework is designed to encourage and support country actions to mitigate risks in the face of a changing climate and would allow for introducing local forest-climate effects into this discourse. It provides a foundation for dealing with multiple spatial and policy scales; incorporates normative issues beyond climate; and provides structures for bottom-up experimentation and information-sharing. And perhaps most relevant in the near term, any party seeking support from the international community to better manage their forests in order to maintain the climate-regulation cooling and rainfall services they provide would certainly be able to do so under the existing adaptation framework, although in light of persistent global underfunding of adaptation, an approach that leans more on mitigation finance flows might be preferred.

SOLAR RADIATION MANAGEMENT: LESSONS FROM A POLICY ANALOGUE

The sections above identify options for considering and potentially incorporating biophysical forest effects on climate within the UNFCCC context and its mitigation/adaptation dichotomy. In this section, we look to the example of solar radiation management (SRM) as a policy analogue for which the locus of governance and policy discussions has so far remained outside of the UNFCCC, and consider lessons for addressing forest-related effects. Box 3.5 defines SRM and summarizes the state of SRM governance.

BOX 3.5 | Solar Radiation Management Overview

Solar radiation management (SRM) refers to a set of potential responses to climate change that would seek to decrease the amount of the sun's energy absorbed by the earth-ocean atmosphere system, thus cooling the planet. We draw a distinction between SRM and carbon dioxide removal (CDR), which are sometimes grouped together as "geoengineering" but have very different physical, economic, and political considerations. SRM does not address the underlying cause of climate change, but rather seeks to address the resulting energy imbalance and rising global temperature. The most common technological proposal for achieving this is *stratospheric aerosol injection*, which would increase the amount of reflective particles or droplets in the high atmosphere through a delivery method such as spraying particles from high-altitude aircraft.

The proposed methods share a common set of risks that create challenges to their effective global governance. SRM would result in uneven effects that do not compensate perfectly for GHG warming, which could put communities at risk through temperature and precipitation effects on agriculture in particular. Combined with regional and national differences in climate optimums, and the potential for ancillary environmental affects (e.g., worsening the ozone hole, or increasing acid rain), SRM at any level of intervention would create winners and losers.

Approaches to global governance of solar geoengineering are still in the early stages of development, with significant forward-looking work by academics but a lack, at present, of a formal intergovernmental venue.[a] Government action has been slow to develop, although the United Kingdom has provided critical funding, and Switzerland recently tabled a resolution (which ultimately failed) to the UN Environment Assembly requesting that the United Nations Environment Programme (UNEP) prepare an assessment report. Several reports have offered principles and pathways forward for the governance of SRM,[b] with particular emphasis on phased approaches with early steps focused on accelerating research and assessment, governance and transparency of research (rather than of deployment), building capacity for research in countries that lack it, pursuing state and stakeholder dialogue and deliberation, and activating and leveraging existing institutions. Through these steps, the international community would establish principles for the governance of SRM deployment based on existing and customary international law, and the institutions necessary for such governance (if new institutions are required).

Sources: a. Florin et al. 2020; b. Reynolds 2019.

The core idea underlying SRM—that we may be able to proactively manage the earth's albedo to reflect a greater proportion of incoming sunlight and cool the climate—is similar to one of the potential objectives for incorporating biophysical forest-climate effects into international climate policy. In fact, surface albedo management—including through land and forest management—is considered an SRM technique. As such, we may look to emerging dialogues around SRM for potential lessons regarding the appropriate venues and policy opportunities to advance proactive management of forests for the purpose of their biophysical global climate contributions.

CONCLUSIONS

Changes in albedo, evapotranspiration, surface roughness, and aerosols as a result of forest cover change are greatly affecting the lived climate experience of large numbers of people around the world, especially in the tropics. They are also accelerating, dampening, or even reversing the global cooling benefits of reduced deforestation and reforestation with patterns that depend largely on latitude. The current global climate policy architecture evolved in a way that leads to these processes being ignored, rather than addressed. And by not accounting for the additional global climate benefits of tropical forests in particular, international climate policy is undervaluing their climate mitigation value and therefore also undervaluing the actions that tropical countries can take to slow and reverse forest loss.

It is useful at this point to return to the questions raised by the heuristic Venn diagram of Figure 3.2: Is there room for biophysical forest-climate processes in the existing UNFCCC framework? If so, where? If not, where could it be stretched to provide room, and how could this stretching be achieved?

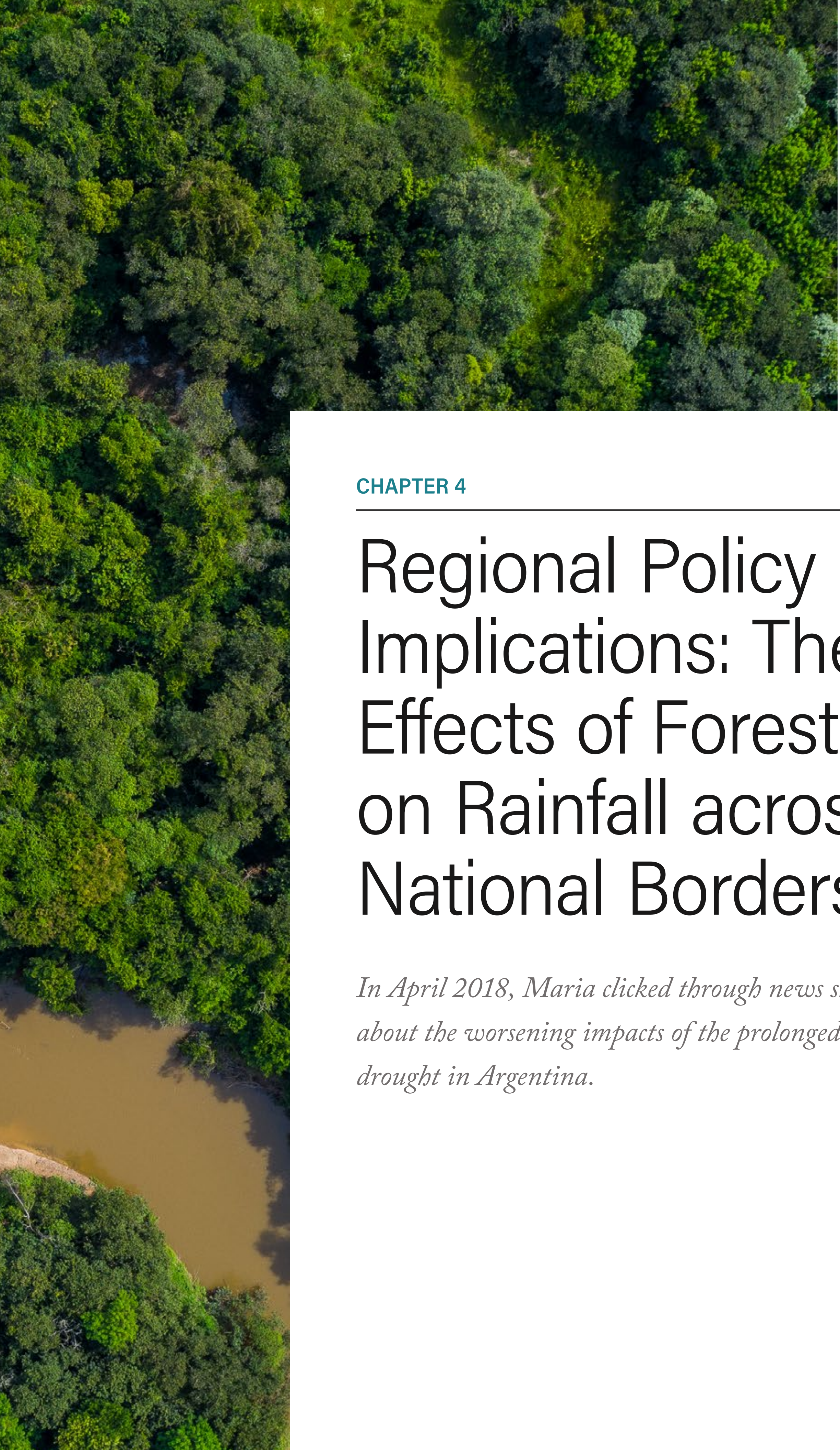
We posit the following conclusions:

- There are several options within the UNFCCC mitigation framework for advancing attention on biophysical effects and the quantification of their role in mitigating global surface temperature increase. While it may be challenging or even undesirable to ultimately expand the formal scope of the UNFCCC mitigation framework to include biophysical processes, introducing the topic into the mitigation discourse—including through existing processes and agenda items—would elevate the topic among policymakers and could spark additional research into quantification of the relative benefits of forests. These include countries introducing biophysical forest-climate effects in the context of their NDCs and related reporting and in the context of REDD+ implementation and finance.

- The "mitigation/adaptation" dichotomy is well established in UNFCCC discourse and decisions, and it would be difficult for forests to "advance apart" rather than "work within" this dichotomy. "Working within" this dichotomy likely means addressing forests' biophysical effects on global temperature through the mitigation policy lens and as part of the discourse on transition pathways, and their local climate stabilization benefits through an adaptation lens and as part of the discourse on resilience.
- The UNFCCC adaptation framework and its implementation mechanisms are generally well suited for consideration of forests' biophysical role in local climate regulation. These include NDCs and NAPs. In particular, any party seeking support from the international community to better manage their forests in order to maintain their climate cooling and rainfall services would certainly be able to do so under its auspices.
- Additional research is needed on the policy and accounting implications of biophysical forest-climate effects. The IPCC could provide an appropriate umbrella for additional research, especially vis-à-vis the challenges of accounting for biophysical global cooling benefits, initiating the work itself, if agreed by member governments or if requested by the Convention's Subsidiary Body for Scientific and Technical Advice (UNFCCC-SBSTA). The first Global Stocktake, which includes the pillars of mitigation, adaptation, and means of implementation, also has science at its core, and could be an option for introducing the additional climate benefits provided by forests for both mitigation and adaptation into the UNFCCC science and policy processes.

The UNFCCC is without doubt the premier venue for global attention to climate change issues. So, while there are significant limitations in the formal frameworks, ultimately, international climate policy is a discursive process—we won't know where it will lead when we get started. And beyond the formal processes, the UNFCCC conferences and surrounding activities present many opportunities outside their technical and textual limitations, by virtue of their role in both attracting and framing global media and political attention on climate change.

Venues outside the global climate policy agenda—such as the SDG process, international forest policy structures, and the restoration agenda along with its Bonn Challenge—may provide some potential for additional attention and analysis of biophysical forest-climate processes but are not explored further in this report. Local, national, or regional policy efforts in alternative venues (such as those discussed in Chapters 4 and 5) may support global policy objectives through bottom-up demand and awareness-raising, but they cannot substitute for the need to have biophysical forest-climate processes on the international climate agenda as well.



CHAPTER 4

Regional Policy Implications: The Effects of Forests on Rainfall across National Borders

In April 2018, Maria clicked through news stories about the worsening impacts of the prolonged drought in Argentina.

An agricultural economist who served as a consultant to several governments and multilateral development banks in the region, Maria was well aware of the implications of the missing rain. Not only would corn and soybean farmers face major losses from reduced grain yields and lower prices for lower-quality crops; there would also be knock-on impacts on other sectors, such as the beef and dairy industries, which depend on grains for animal feed, and the truckers who transport it. Indeed, due to the importance of rainfed agriculture to the country's economy, the drought had already reduced Argentina's economic growth forecast by a full percentage point, frustrating macroeconomists in the government and at development banks who were working together to reduce fiscal deficits and control inflation.

Maria felt as though she'd seen this movie before: just 10 years earlier in 2008, a major drought in Argentina had generated lots of consulting assignments. Policymakers had been eager for advice on how to address the demands of distressed farmers seeking relief. The difference this time was that the drought was more commonly being attributed to climate change, even by the macroeconomists. Increasingly, Maria's consulting jobs focused on assessing climate risks and helping to program funds earmarked for adaptation and increased resilience—reflecting a gradual mainstreaming of climate change considerations into the country portfolios of development banks.

But Maria had a nagging sense that by focusing only on what the government of Argentina could do to address the drought, the development banks were missing a key piece of the puzzle: that the lack of rainfall might be connected to deforestation, including what was happening in neighboring Brazil. Forty years earlier, scientists had documented the role of the Amazon Rainforest in recycling moisture through evapotranspiration, affecting rainfall across the continent. And just a few weeks ago, Maria had read an editorial published by prominent scientists Tom Lovejoy and Carlos Nobre, warning that the Amazon Rainforest was approaching a "tipping point" beyond which conversion of the ecosystem from forest to savanna would become irreversible. Maria noted the authors' linkage of this risk to the importance of moisture from the Amazon to rainfall in central-eastern Argentina.

Could it be that that the loss of forests in Brazil was already contributing to Argentina's drought?

This imagined story draws on news reports regarding the 2017–18 drought (e.g., AP 2018) and Lovejoy and Nobre (2018).

Scientists have good evidence that shifting rainfall patterns across South America can be traced back to deforestation happening hundreds of miles away in the Brazilian Amazon. The Brazilian Amazon Rainforest acts as a sort of "water tower," contributing a portion of the annual precipitation in the downwind countries of Bolivia, Paraguay, Uruguay, and the central-eastern part of Argentina through a process known as terrestrial moisture recycling (TMR), whereby evapotranspiration from land enters the atmosphere, travels with prevailing winds, and falls out as precipitation (Keys et al. 2017). The fate of agricultural production in Argentina—a $43 billion/year industry (FAO 2017)—is thus hostage to forest cover changes in its neighbor Brazil.

International law, customary law, and regional policy venues have emerged to help address issues similar to this one, where the actions in one country have the potential to cause harm to neighboring countries. For example, river basin treaties are commonly used to establish principles of surface water use and management among nations. But no such venue exists for the farmers of Argentina—or their representatives in the government—to address the disruption in precipitation through collaboration with the Brazilian government.

In this chapter, we look more closely at the science and potential impacts of regional terrestrial moisture recycling in tropical forest areas, with a focus on the Amazon and

Congo Basins. These two basins host the world's two largest expanses of tropical forest. Both are considered "tipping elements" for the entire Earth system, as changes in rainfall due to deforestation and climate change could result in nonlinear changes to habitat conditions and climate around the globe (Wang-Erlandsson et al. 2022). We then analyze gaps and opportunities in policies and institutions necessary to address TMR and provide illustrative examples for how existing transboundary water governance and policy venues could be improved to incorporate TMR considerations and/or complemented by other actions.

SCIENCE OVERVIEW

Over the past 10 years, the process of TMR at the regional scale has been well studied and modeled, using, for example, improved hydrological and atmospheric moisture tracking models as well as improved remote sensing and rain gauge data (Keys et al. 2012, 2016, 2017, 2019; Gebrehiwot et al. 2019; Lawrence and Vandecar 2015; Mahmood et al. 2014; Spracklen et al. 2012, 2018; Spracklen and Garcia-Carreras 2015; Staal et al. 2018, 2020a; Te Wierik et al. 2021; van der Ent et al. 2014; Wang-Erlandsson et al. 2018). Although temperate and dryland forests are less well studied, recent research shows that tropical forests are especially important as producers of precipitation for the forests themselves as well as for downwind ecosystems spanning entire continents. Many forests also have a buffering effect on the variability of precipitation, with a higher percentage of an area's precipitation originating from forests associated with less variable amounts of precipitation each month. This buffering effect is strongest for tropical forests, where on average if areas receive 50 percent of their precipitation from forest sources, they will have 69 percent lower variation in precipitation (O'Connor et al. 2021a). And while this chapter focuses on the transboundary policy implications of TMR in two tropical regions, the phenomenon is relevant to many types of forests and across scales.

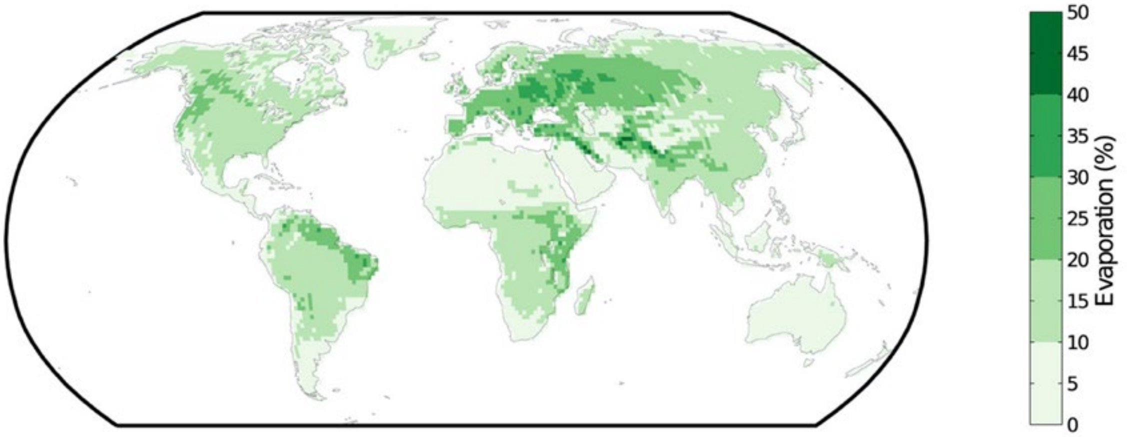
The main mechanism driving TMR at the regional scale is the biophysical mechanism of evapotranspiration (described in Chapter 2). In general, forests have higher rates of evapotranspiration compared to other land-use types due to evaporation directly from leaves (i.e., interception evaporation) and through transpiration of water that is stored in deeper soil layers and pumped through the leaves during photosynthesis (Staal et al. 2020a; van der Ent et al. 2014). Moisture produced from forests through evapotranspiration is converted into water vapor, which is carried by winds across continents and oceans and falls as precipitation (Keys et al. 2017). This movement of moisture is sometimes referred to as "flying rivers" (Welch 2019). One study found that air masses that travel over tropical forests produce almost twice the amount of rainfall compared to air masses traveling over nonforest areas (Spracklen et al. 2012). It is estimated that, on average, 40 percent of precipitation on land originates from evapotranspiration that came from land and travels over a range of 500–5,000 km (van der Ent et al. 2010; van der Ent and Savenije 2011). Deforestation results in a decrease in evapotranspiration, which decreases precipitation in downwind areas, on a magnitude similar to the effect that is predicted to result from global climate change (Spracklen et al. 2018).

The upwind atmosphere and area of land from which this moisture originates is commonly referred to as a precipitationshed, and the downwind area of land where this moisture is deposited is referred to as a sink or an *evaporationshed* (Keys et al. 2012; Wang-Erlandsson et al. 2018). Figure 4.1 below provides global maps of atmospheric moisture sources and sinks from ecosystems (i.e., terrestrial vegetation). These diagrams highlight that tropical forests are important both at the local scale (they can produce much of their own precipitation through "local recycling") and as providers of rainfall at the regional scale. So, deforestation in the Brazilian Amazon will impact the Amazon Rainforest itself, as well as downwind countries in South America (further explored in Box 4.1). Other regions that receive a high degree of TMR precipitation include east and central Asia and a significant portion of Canada (Keys et al. 2016).

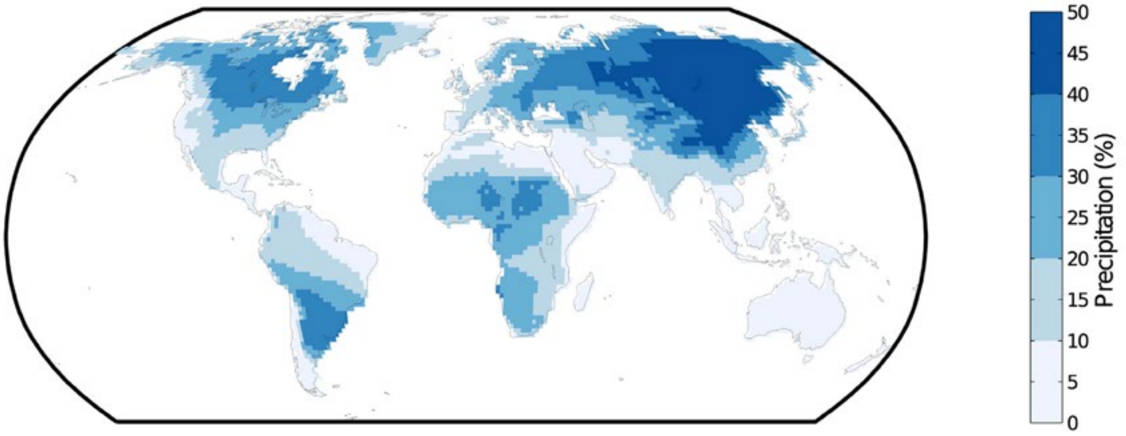
There are several processes that affect the relationship between forest cover and regional precipitation. As described in Chapter 2, forest vegetation mediates moisture, energy, and trace-gas fluxes between the earth's surface and the atmosphere. Changes in vegetation lead to changes in biophysical mechanisms including albedo, surface roughness, and aerosols, and these changes result in changes in land-atmosphere moisture fluxes (Spracklen et al. 2018). The extent of the change in precipitation due to deforestation thus depends on several factors including geographic location and prevailing winds; type and extent of land-use change (e.g., what land uses are forests being converted to, is deforestation fragmented or occurring over continuous

FIGURE 4.1 | Global Terrestrial Moisture Recycling

A) ECOSYSTEMS SUPPLYING ATMOSPHERIC MOISTURE



B) ECOSYSTEMS RECEIVING ATMOSPHERIC MOISTURE



Source: Keys et al. 2016.

swaths of land?); dry vs. wet years; and the percentage of precipitation that comes from oceanic and continental origin (Gimeno et al. 2020; Keys et al. 2018, 2019; Lawrence and Vandecar 2015). Forests' buffering impact on precipitation variability also depends on several factors including land cover composition, climate and topography, and proximity to oceans (O'Connor et al. 2021a). Tropical forest basins such as the Amazon and Congo reduce precipitation variability due to their dense and expansive tree cover and high rainfall and evapotranspiration fluxes, whereas temperate broadleaf forests have a relatively weak buffering effect on variability due to a low average tree cover and shallower rooting depths. Boreal forests, which experience below-zero winter temperatures, show no buffering effect (O'Connor et al. 2021a).

While the direction and relative magnitude of TMR at the regional scale is sufficiently clear and indicative of the vulnerability of a region's rainfall to changes in land use, experts have highlighted some key modeling and science uncertainties that should be addressed with future research. For one, there needs to be greater reconciliation between local and regional forest-atmospheric models. Second, there are recognized scientific uncertainties with *general circulation models* (GCMs), hydrological and atmospheric moisture models, as well as historic rain gauge data. For example, processes of convection, cloud formation, and aerosol interactions have not been well represented in most models

(Lawrence and Vandecar 2015). Further, more study is needed on the role of forests in promoting cloud formation, the role of forest-produced aerosols as inducers of rainfall, and the role of forests and land-use change in altering albedo and *leaf area index* (Ellison and Speranza 2020; Spracklen et al. 2018). Another area that lacks certainty is the possible impact of TMR on the rising temperature–induced changes to the water cycle. Recently, rising global temperatures have caused an increase in water vapor in the atmosphere, which has led to a positive feedback cycle of warming due to water vapor's role as a GHG (Hansen 2008). It is possible that TMR could facilitate the return of this water vapor to the land as localized rainfall, but more research is needed to understand its effect.

POTENTIAL IMPACTS OF RAINFALL DISRUPTIONS ON AGRICULTURAL PRODUCTION AND WATER STRESS

Reductions in regional precipitation and changing precipitation patterns due to deforestation would likely have severe impacts on food, water, and energy security, jobs, and human health for hundreds of millions of people around the world, especially in regions with limited options for adaptation to a drier climate. A recent study that reviewed five major breadbasket regions of the world found that they are all susceptible to reductions in moisture due to land cover change, which could lead to a potential crop yield reduction of 1–17 percent. This level of crop yield reduction is on par with that predicted to occur with greenhouse warming and would represent a severe food supply disruption (Bagley et al. 2012). Ukraine represents only 3 percent of the world's grain supply, but disruption of that supply in 2022 threatened food security around the world and has caused a spike in food prices (World Bank Group 2022).

Furthermore, these impacts may be felt almost immediately as TMR in tropical forests is known to change rainfall levels at seasonal and annual timescales (Staal et al. 2020a), although more research is needed to account for internal climate variability. According to recent studies, residence times for water in the atmosphere range from 3 to 20 days (Bodnar et al. 2013; van der Ent and Savenije 2011; van der Ent et al. 2014). The Argentina story highlights the potential scale of impact of deforestation in the Amazon for this major soybean and maize–producing country: the 2017–18 drought, which models suggest was exacerbated by Amazon deforestation, resulted in crop losses of more than $1.5 billion, and an overall impact on the economy of about $4.6 billion (Bert et al. 2021).

Indeed, declines in agriculture production caused by deforestation-induced rainfall disruption could compound declines attributable to global climate change, amplifying the scale of humanitarian crises. IPCC scenarios project that hundreds of millions of people in dryland areas will be exposed to multiple impacts of climate change—including water stress, drought, and habitat degradation—even at levels of warming limited to 1.5°C (IPCC 2019b). The implications of such exposure as a catalyst for migration and conflict are illustrated by the prolonged drought in Syria (Abel et al. 2019). Crop failures led to the displacement of rural families (estimated to be up to 1.5 million people) to urban areas, exacerbating other social stressors such as unemployment and inequality and leading to unrest (Kelley et al. 2015).

The risk of urban water stress is also critically linked to TMR. Keys et al. (2018) found that 19 out of 29 megacities around the world depend on TMR for more than a third of their water supply, with eight cities depending on TMR for more than half of their water supply. Buenos Aires, Argentina, and Rio de Janeiro and São Paulo, Brazil, receive over 45 percent of their respective watershed's precipitation from upwind land areas. These cities are already facing droughts and water quality problems, so a further decrease in water availability places their water supply systems at higher risk, along with the millions of people who depend on them (Feltran-Barbieri et al. 2018; Ozment et al. 2018).

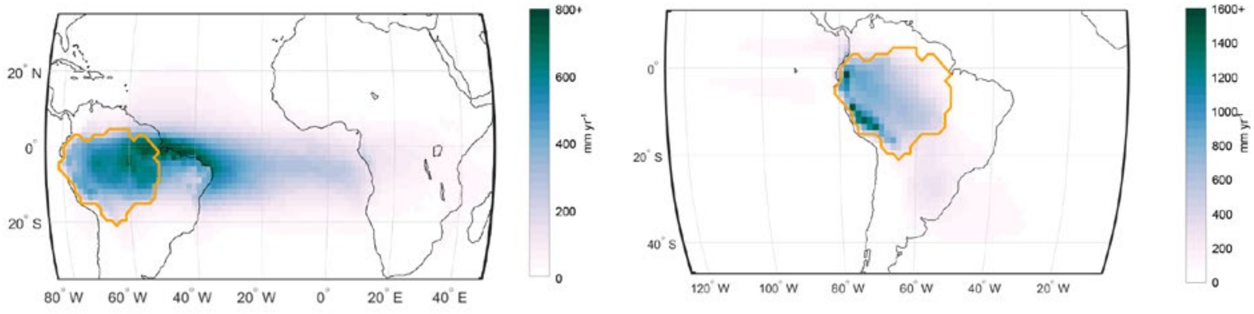
Many of these cities lack the proper infrastructure and risk response mechanisms to quickly adapt to large changes in water supply. While impacts are worse in dry years, the relationship between deforestation of tropical forests and rainfall is not likely to be linear. For example, if the Amazon Basin were to breach the "tipping point" mentioned above, the conversion of forest to savanna could rapidly accelerate the decrease in precipitation to downwind countries. These impacts are further explored below in Boxes 4.1 and 4.2 for the Amazon and Congo Basins, respectively.

BOX 4.1 | The Amazon Basin—A Water Tower for the Region

The Nature and Scale of TMR

The Amazon Basin is the world's largest tropical forest, covering an area of more than 5.3 million square kilometers (km^2). It stretches across nine countries in South America, with the majority—60 percent—located in Brazil (See Fig. B4.1.1A). The Amazon Rainforest is a powerhouse of ecosystem services. It has been well studied for its provision of biological diversity; water filtration; carbon sequestration; and, increasingly, precipitation within the Amazon Basin itself and to other downwind areas in greater South America.

Figure B4.1.1 | Amazon Basin: Basin Forest Area (A), Precipitationshed (B), and Evaporationshed (C)



(B) Precipitationshed for the Amazon River Basin

(C) Evaporationshed for the Amazon River Basin

Note: Orange boundaries in (b) and (c) represent river basin boundaries.

Sources: GFW 2020; Wang-Erlandsson et al. 2018.

BOX 4.1 | The Amazon Basin—A Water Tower for the Region (cont.)

In parts of the Amazon Basin, up to 50 percent of precipitation originates from the forest itself [c, d] with one study finding that 64 percent of all regionally recycled water has been transpired by the trees of the Amazon and that transpired moisture can precipitate and evapotranspirate repeatedly over forests.[e] Additionally, recent studies have shown the importance of the Amazon Rainforest in buffering against droughts. One study found that transpiration within the Amazon Rainforest appears to be highest during dry season.[e] A study of the Rondonia region located in the central region of the Amazon found that during drought years (which are triggered by ocean conditions like El Niño Southern Oscillation events or high sea surface temperature anomalies), the moisture contribution of forests remained stable while moisture from oceanic and nonforest sources decreased.[d] On a continental scale, 63 percent of evaporation from the Amazon rains down over land.[e] Brazil acts as a key source of moisture for countries in the southeast of South America, providing 13–32 percent of annual precipitation downwind to Bolivia, Paraguay, Uruguay, and Argentina (Keys et al. 2017). Figure B4.1.1 provides maps of the precipitationshed and evaporationshed for the Amazon,[b] demonstrating this water tower effect. The largest source of precipitation is located along the eastern portion of the Amazon Basin, with the highest precipitation sink located along the western portion; this assessment was also supported by Spracklen et al. (2018).[g] If deforestation continues on a business-as-usual trajectory, by 2050 rainfall could be reduced by 12 and 21 percent in the dry and wet seasons, respectively.[g]

The Amazon Tipping Point

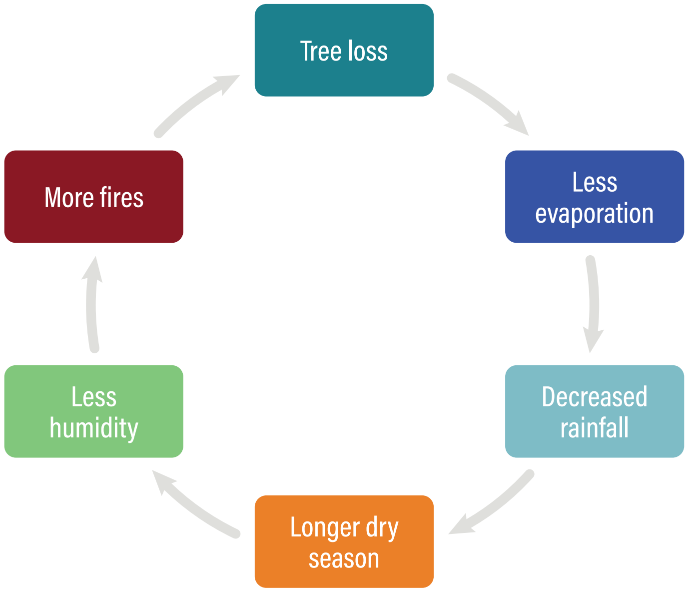
The impacts of a reduction in rainfall across Brazil, Bolivia, Paraguay, Uruguay, and Argentina stemming from deforestation of the Amazon Basin are only beginning to be explored.[h] Nevertheless, early estimates are that those impacts could be significant. For example, a recent study focused on the southern Brazilian Amazon found that under a weak governance scenario (defined as the continued dismantling of Brazil's conservation policies along with strong political support for environmentally damaging agricultural practices and implicit economic incentives for illegal deforestation), the region could suffer agricultural losses tied to soy and beef production valued at $1 billion annually.[i] Another recent study estimated changes to agricultural productivity within the Amazon due to deforestation-induced rainfall reduction and found that soybean and beef production would experience an annual per hectare rent loss of up to 30 percent.[j]

There is a renewed sense of urgency to understand these impacts due to increased evidence that the Amazon Rainforest may be approaching a tipping point beyond which the majority of the Amazon (50–70 percent) would be committed to ***savannization***, a process of permanent conversion to nonforest ecosystems described below.[k, l, m] The Amazon Basin has recently experienced an alarming incidence of forest fires, and other extreme events such as high heat, droughts, and floods, which are causing some scientists to think the tipping point could be reached in the very near future.[k] This tipping point is likely to be nearly irreversible.

Just a few years ago, it was thought that this tipping point would be reached at a deforestation level of 40 percent of the Amazon Rainforest.[n] However, in light of the "negative synergies between deforestation, climate change, and widespread use of fire," scientists warn that the tipping point is likely closer to the loss of 20–25 percent of total forest area (Lovejoy and Nobre 2018).[o] The region has already been 18 percent deforested,[p] and 2021 saw the highest annual rate of deforestation in a decade in the Brazilian Amazon.[q] Recently developed theory suggests that Earth systems such as the Amazon ***may*** be able to live on borrowed time before tipping occurs, but it is unclear both whether borrowed time amounts to decades or just years, and what degree of degradation or deforestation will tip the system into irreversible savannization.[r] Figure B4.1.2 provides a conceptual model demonstrating a self-propagating "natural" cycle that may take over in the Amazon Rainforest due to climate change and deforestation.

BOX 4.1 | The Amazon Basin—A Water Tower for the Region (cont.)

FIGURE B4.1.2 | Amazon Tipping Point



Once Amazon Rainforest conditions are degraded sufficiently due to human causes, a self-propagating "natural" cycle takes over. The challenge for scientists is pinpointing the timing of the rainforest-to-savanna tipping point. Image by Shanna Hanbury.

Source: Hanbury 2020.

An increased level of deforestation would lead to an even greater loss in rainfall, which would lengthen the dry season, resulting in more forest fires and hence more tree loss. This drought-deforestation feedback would thus amplify impacts on food, water, energy (e.g., hydroelectricity generation), and job security across South American countries, in addition to health impacts from more fires and poorer water quality. In other words, expanding Amazon deforestation in favor of agribusiness interests as a development strategy would be self-defeating as it would lead to a reduction in agricultural and livestock productivity and associated jobs, due to this cycle.[s]

A recent study on this drought-deforestation feedback[t] examined the feedback between drought and deforestation in the Amazon and found TMR contributes roughly 4 percent to the lengthened dry season, with global climate change having the largest impact. The study also found that while this drought-deforestation connection is relatively small, it is a reinforcing feedback that could intensify with greater deforestation. Climate change is contributing to the increased duration and frequency of droughts, which increases the risk of wildfires and deforestation. Additionally, deforestation is making dry seasons more intense due to reduced regional rainfall. This effect is felt most strongly in the southwestern part of the Amazon, with the remaining contribution driven by climate change and natural variations such as the El Niño Southern Oscillation.

Furthermore, the decrease in precipitation in other South American countries, such as Argentina, would lead them to experience reductions in their agricultural productivity or shifts in agricultural production zones. As described further in Chapter 5, these changes in rainfall are also likely to be accompanied by warmer daytime temperatures, which would place further stress on crops.[h]

Sources: a. GFW 2020; b. Wang-Erlandsson et al. 2018; c. Keys et al. 2019; d. Mu et al. 2021; e. Staal et al. 2018; f. Tuinenburg et al. 2020; g. Spracklen et al. 2012; h. Lawrence and Vandecar 2015; i. Leite-Filho et al. 2021; j. Strand et al. 2018; k. Lovejoy and Nobre 2019; l. Hanbury 2020; m. Boulton et al. 2022; n. Nobre et al. 2016; o. Lovejoy and Nobre 2018; p. WWF 2021; q. Imazon 2021; r. Ritchie and Roser 2021; s. Oliveira et al. 2013; t. Staal et al. 2020b.

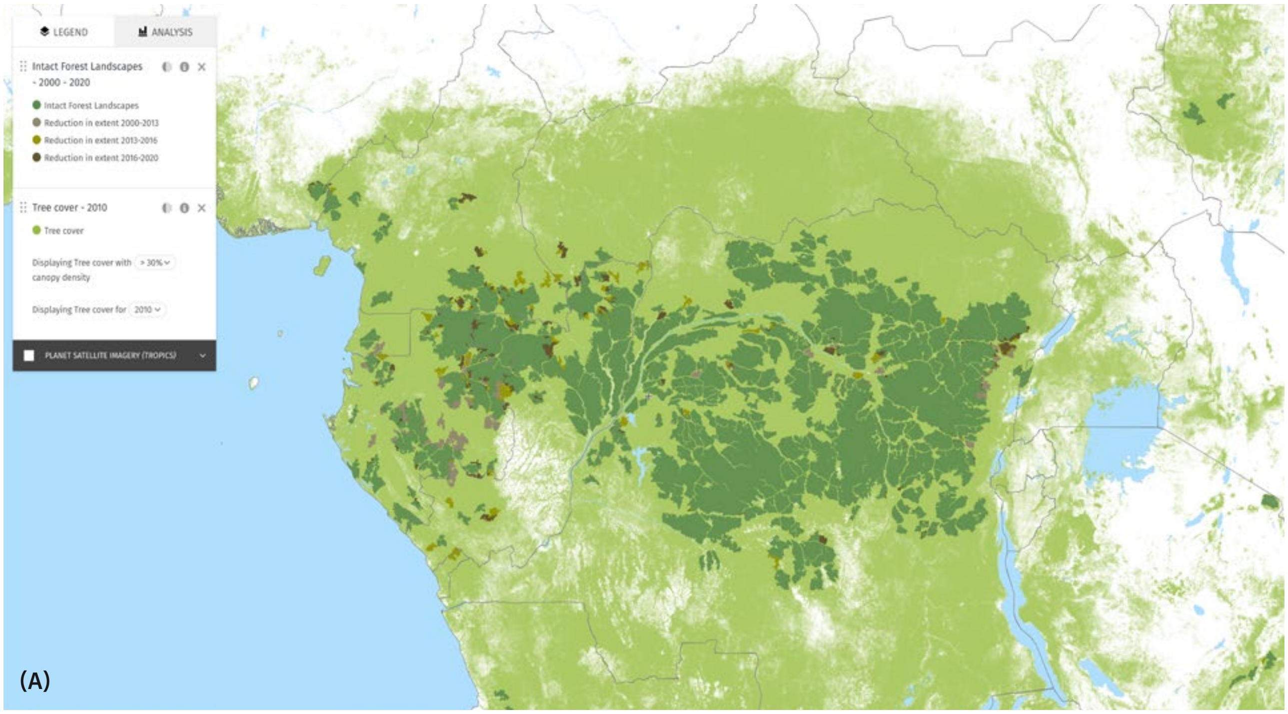
BOX 4.2 | The Congo Basin: Is Deforestation a Threat to Water Security in the Region?

The Nature and Scale of TMR

The Congo Basin (Figure B4.2) is the world's second-largest tropical forest, covering 13 percent of the total area of Africa at over 2 million km². The basin covers parts of six countries: the Democratic Republic of the Congo (DRC), Republic of the Congo (ROC), Central African Republic (CAR), Cameroon, Equatorial Guinea, and Gabon, with the DRC containing 61 percent of the basin.[a] Despite its importance, the region is critically understudied compared to the Amazon in terms of how it will respond to climate change, partially due to a lack of rainfall data and to modeling uncertainties.[b]

There have been some attempts to fill this gap in research in the last couple of years. Dyer et al. (2017) studied the sources of precipitation in the Congo Basin and found that the Indian Ocean and local evaporation are the two most important sources, followed by evaporation from other regions in Africa and the Atlantic Ocean.[c] The study estimated the mean TMR ratio at 25 percent in both rainy seasons, with an annual ratio of 28 percent. Sori et al. (2017) estimated the mean TMR ratio to be as high as 50 percent.[d] Wang-Erlandsson et al. (2018) mapped the precipitationshed and evaporationshed of the Congo Basin Figure B4.2 (B) and (C), showing the strongest precipitation source is in the east and the strongest precipitation sink is the western Congo.[e] Sonwa et al. (2020) found that the forest-related water cycle of the Congo Basin is unstable and gradually changing, causing rainfall to decrease and waterflow to be disturbed as a result of changing temperatures.[f] An effort supported by the World Bank to improve understanding of the forest-water interactions in the Congo Basin is described in Box 4.4 below.

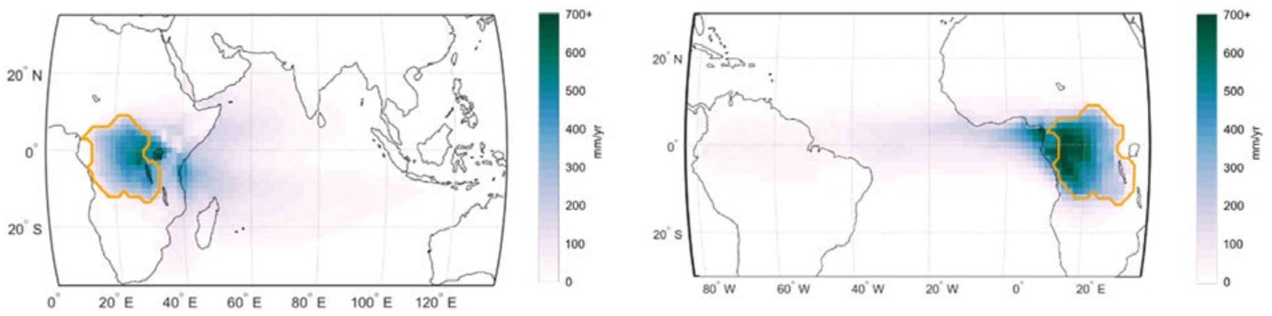
FIGURE B4.2 | Congo Basin Forest Area (A), Precipitationshed (B), and Evaporationshed (C)



Displaying Tree cover with > 30% canopy density

Displaying Tree cover for 2010

BOX 4.2 | The Congo Basin: Is Deforestation a Threat to Water Security in the Region? (cont.)



(B) Precipitationshed for the Congo River Basin

(C) Evaporationshed for the Congo River Basin

Note: Orange boundaries in (b) and (c) represent river basin boundaries.

Sources: GFW 2020 and Wang-Erlandsson et al. 2018.

On a regional scale, deforestation in the Congo Basin would likely lead not only to decreases in evapotranspiration but also to changes in monsoon circulation patterns.[h] Forest loss could also lead to modification of precipitation in other areas of Africa such as the Sahel region, which has been shown to receive moisture from West Africa via the African Easterly Jet.[i, j, k, e] Other recent work has highlighted a possible connection between the Congo Basin and the Ethiopian Highlands and Nile River Basin, although more analysis is needed.[a] Based on simulations of complete deforestation of the Congo, regional rainfall has been projected to be reduced by roughly 8 to 40 percent with a median of 16 percent.[m]

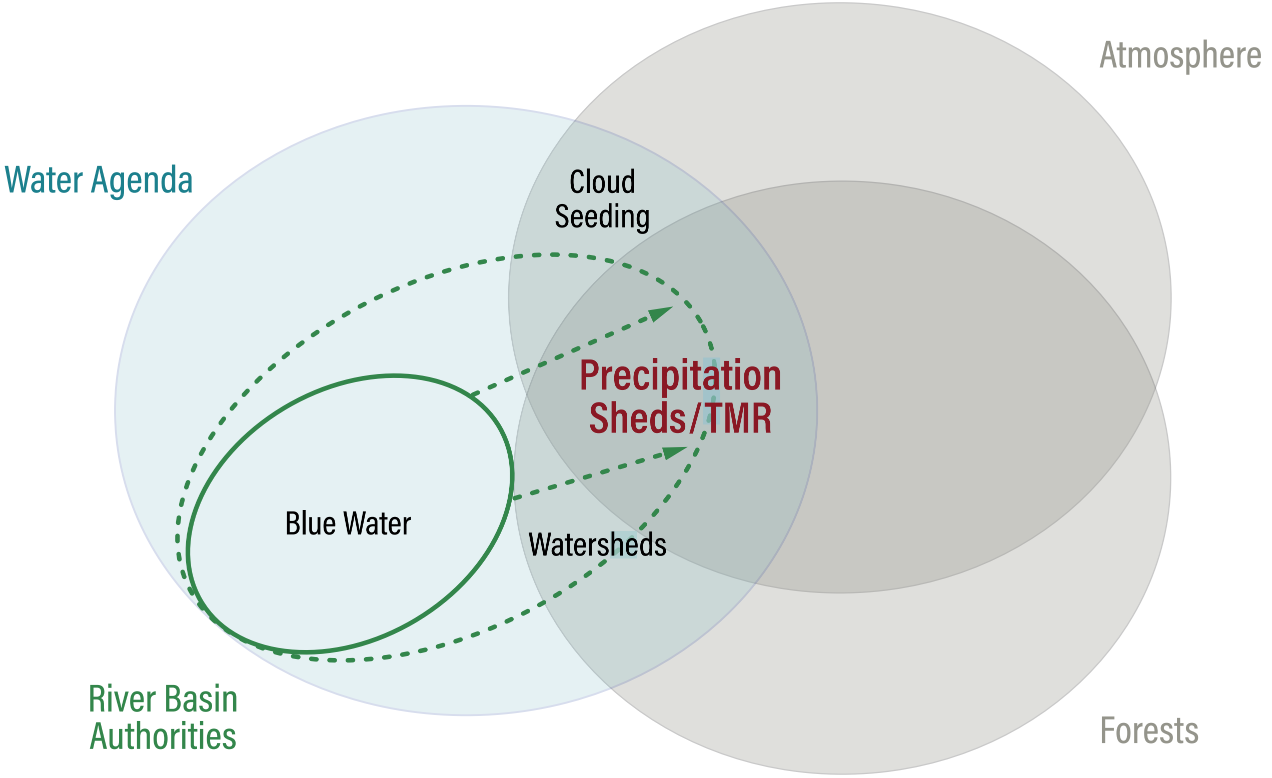
While the rate of deforestation in the region is currently low compared to the rate of forest loss in the Amazon Basin, the Congo Basin may also have a tipping point beyond which it would be committed to a path of conversion to a lower-biomass forest.[n] Given its high local precipitation recycling ratio (i.e., the amount of precipitation in a region that is formed from evaporation in that same region), forest cover could be a limiting factor for future precipitation.[c]

Impacts

The potential impacts of forest cover changes in the Congo Basin through TMR are not as well studied as those in the Amazon Basin.[o] Dyer et al. (2017) state that since forest cover in the Congo could be a limiting factor for future precipitation, there could be a feedback loop between deforestation and decreasing rainfall.[c] The Sahel region could face increasing landscape degradation with increasing deforestation of the Congo.[i] Additionally, cities within the evaporationshed could be impacted. As an example, in the DRC, Kinshasa's water supply would be at particular risk. In wet years the city's watershed receives more than 50 percent of its precipitation from the Congo Basin.[o]

Sources: a. Gebrehiwot et al. 2019; b. Creese et al. 2019; c. Dyer et al. 2017; d. Sori et al. 2017; e. Wang-Erlandsson et al. 2018; f. Sonwa et al. 2020; g. GFW 2020; h. Akkermans et al. 2014; i. Ellison and Speranza 2020; j. Keys et al. 2016; k. van der Ent et al. 2010; l. Gebrehiwot et al. 2019; m. Spracklen et al. 2018; n. Zhou et al. 2014; o. Keys et al. 2018.

FIGURE 4.2 | Regional Governance Overview



Note: TMR = Terrestrial moisture recycling.

Source: Authors.

EXISTING INSTITUTIONAL AND POLICY GAPS

Terrestrial moisture recycling lies at the intersection of atmospheric, forest, and water law and policy (Te Wierik et al. 2019). No governance mechanisms exist today within forest, water, or atmospheric governance or their intersections to incorporate TMR into water and land management decisions at the regional scale (Ellison et al. 2018; Te Wierik et al. 2019). Additionally, TMR lacks consideration in the popular planetary boundaries framework developed by the Stockholm Resilience Centre, which aims to provide Earth system boundaries in which humanity can continue to develop and thrive for generations to come (Wang-Erlandsson et al. 2022; Steffen et al. 2015). In this section, we provide a brief and selective global overview of *regional regulatory instruments* (e.g., transboundary agreements) and market-based instruments to govern these three realms in order to highlight their intersections and identify where gaps exist related to TMR. Figure 4.2 illustrates some of these intersections.

Transnational Governance of Surface Water

Many transnational authorities and agreements exist to govern surface water (often referred to as "blue" water) and groundwater. The management boundary is generally the water basin—whether it be a river basin or watershed—and the resource base governed is typically a river, lake, or aquifer. A scan of transboundary water institutions and organizations developed over the last 50 years suggests that there are a

handful of conventions and directives that set principles and norms for blue water governance, including the 1992 UN Helsinki Convention, the 1997 UN Convention on the Non-Navigational Uses of International Watercourses, and the European Union Water Framework Directive (Te Wierik et al. 2019). Principles established by these conventions cover key issue areas including sovereignty, equity, avoidance of harm, participation, prior informed consent, and conflict resolution (Te Wierik et al. 2019).

To date, there are approximately 285 independent *transboundary water agreements* that together govern 70 percent of the world's transboundary basin area (Giordano et al. 2014). Several transboundary intergovernmental organizations, including river basin authorities such as the Mekong River Commission, exist to enforce these conventions and agreements. Many of the transboundary water agreements and organizations operating today have been influenced by principle-setting at the international level; have adopted an integrated water resources management (IWRM) framework; and have been focused exclusively on blue water and on issues relating to drinking water, sanitation, and irrigation (Ellison et al. 2018; Te Wierik et al. 2019). While such treaties and agreements seem to be evolving to move beyond consideration of the single issue of water allocation to considering environmental issues and greater stakeholder involvement, consideration of TMR is still completely absent (Ellison et al. 2018; Giordano et al. 2014; Keys et al. 2017).

It should be noted that even traditional regional and international water governance for blue water remains a serious challenge for many countries, including for those in the Congo and Amazon Basins (Te Wierik et al. 2019). One problem is that these agreements focus only on riparian countries, and not even all riparians in a basin are necessarily parties to applicable treaties. Only about a quarter of all treaties cover an entire basin (Giordano et al. 2014). For example, the effectiveness of the Mekong River Commission has been hampered by the fact that the most significant upstream country, China, is not a member (Backer Bruzelius 2007). The Mekong River Commission further illustrates the limited abilities of such agreements to enforce compliance by member states (Ellison et al. 2018). Although member states are required to notify other members of planned projects that could have regional implications, the commission cannot enforce compliance with that requirement, and has no means to block such plans (Suhardiman et al. 2015). And analysts have noted that "when uncertainty is high, present impacts relatively light, and projected negative consequences perceived as distant in time, momentum for change is slow" (Grumbine 2018).

Transboundary Governance of the Atmosphere

At the intersection of water and atmospheric governance, discussion has largely centered on weather modification such as *cloud seeding*. Two conventions address weather modification—the 1977 Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques and the 1992 Convention on Biological Diversity—and aim to constrain the potential of countries to use weather modification in a hostile manner (Ellison et al. 2018). Neither addresses the effects of land-use change on TMR.

In addition, two agreements that address transboundary air pollution are relevant, one connected to rainfall and the other connected to forests, although neither addresses TMR. The United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution was established in 1979 among 32 European countries, the United States, and Canada to address the acid rain problem. As described further below, the convention provides a useful policy analogue for key aspects of collaborative TMR management (Ellison et al. 2018).

The Association of Southeast Asian Countries (ASEAN) Transboundary Haze Agreement, established in 2002 to address smoke from forest fires in the Southeast Asia region, appears less promising as a model. Its effectiveness was constrained by political economy factors within and between countries, linked to the underlying causes of the fires, as well as by the "ASEAN way," which prioritizes national sovereignty of members over the collective interests of countries in the region (Varkkey 2012; Heilmann 2015). However, cooperation across stakeholder groups, including private companies and civil society organizations in Singapore and Indonesia, to undertake fire mitigation activities illustrate the potential of hybrid partnerships to address the causes of transboundary air pollution in ways that sidestep the political sensitivities of formal governance processes (Miller et al. 2020).

Transboundary Governance of Land Use Linked to Water

Much of the effort to establish transboundary governance of forests (and associated literature) focuses on biodiversity conservation, especially management of habitat for migratory species. However, because of its greater relevance to governance of TMR, we limit our scope here to governance of land use linked to water provision (Miller et al. 2020).

As demonstrated by the science on TMR—as well as long-standing work on surface waters—blue water availability is intricately linked with land use and land-use change, especially forests and agriculture. Governance mechanisms and authorities addressing the intersection of water and land-use governance have largely been established at the watershed scale, focusing on the relationship between upstream forest health and downstream water quality and blue water quantity. A growing number of forest restoration projects across the world have integrated water resources management and policies (Filoso et al. 2017).

One of the most widely used market-based mechanisms for integrating forest and water governance is the *payments for ecosystem services (PES) schemes*. The central idea behind PES is that those who benefit from provision of an ecosystem service should compensate those who are responsible for maintaining the quality of that ecosystem service—in this case that water users should compensate upstream communities who protect and maintain forests. Hundreds of PES schemes have been established since the 1990s, along with innovative financing mechanisms to support these schemes, such as green bonds and resiliency bonds (World Bank Group 2020). Additionally, the literature examining criteria for success and economic and financial costs and benefits is increasing—providing plenty of evidence for how to set up a successful scheme and how to monetize and finance the value of ecosystem service provision (Wunder and Wertz-Kanounnikoff 2009; Wunder and Borner 2012). Recent research highlights the importance of participatory approaches and strong community engagement as being a key success factor (Min-Venditti et al. 2017).

> Blue water availability is intricately linked with land use and land-use change, especially forests and agriculture.

However, experience with PES schemes that cross international borders remains limited, and there are no PES schemes in existence today that consider TMR (Ellison et al. 2018). The most relevant policy analogue, Reducing Emissions from Deforestation and forest Degradation, or REDD+, the framework under the UNFCCC described in Chapter 3, remains largely untested at scale (Seymour and Busch 2016).

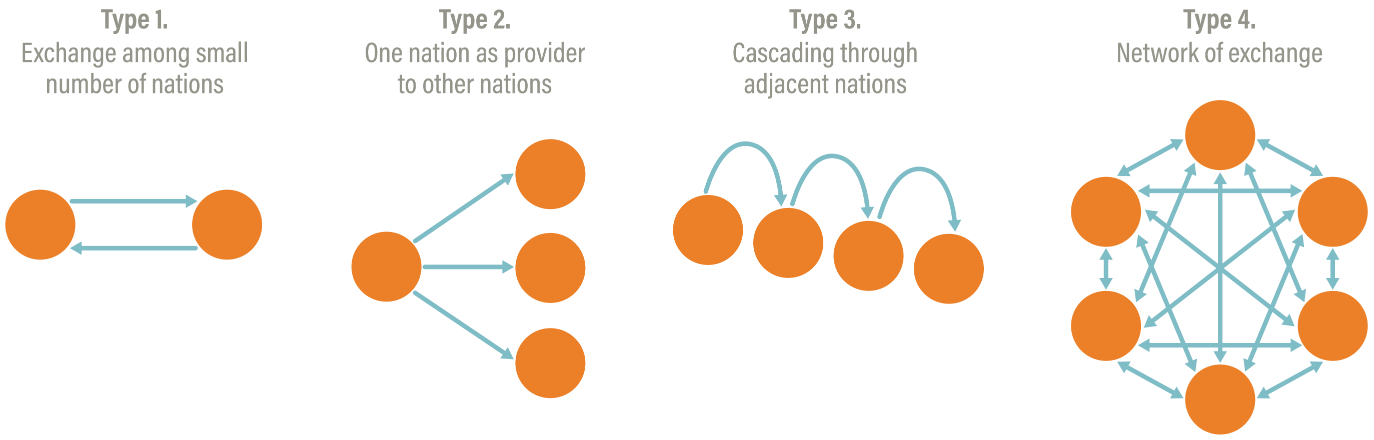
Policy Directions for Institutional Development

In this section we explore policy directions for addressing the institutional and governance gaps for TMR outlined above. We focus on four illustrative examples of directions that show promise and deserve further exploration for their viability. We do not aim to be prescriptive considering the diversity in land use, climate, hydrology, and sociopolitical contexts across regions, but rather aim to provide a sense of the general direction that transboundary resource governance needs to move toward the regional scale. Additionally, the examples are not meant to be mutually exclusive, and there may be a natural phasing of them depending on the region.

To start, we consider the various relationships for moisture recycling exchanges among countries, which help disentangle some of the important political economy considerations that are the context for establishing appropriate policy directions. Keys et al. (2017) usefully outline a typology for these moisture flow regimes as demonstrated in Figure 4.3, from Type 1 or an exchange of atmospheric water across a small number of nations to Type 4 or a complex network of exchange across multiple countries. On one end of the spectrum, moisture is exchanged among a small number of countries, making transboundary governance of TMR more straightforward and manageable. At the opposite end, we see a complex network of moisture exchange between multiple countries. Understanding the type of moisture network and which countries are involved will be important for determining the most appropriate policies, laws, and institutions to be harnessed or created moving forward.

For example, in Type 2 and Type 3 situations, the political and economic power differentials between the single countries (which control the precipitationshed) and downwind countries (which suffer the effects of disrupted rainfall) will affect the feasibility of various policy options and associated economic instruments. For example, if the country controlling the precipitationshed is richer and more powerful than downwind countries, it is unlikely that a transnational PES scheme whereby the upwind country is paid by downwind countries is a viable option. At the same time, the fraught history of UNFCCC negotiations regarding the issue of "Loss and Damage" suggests that

FIGURE 4.3 | Conceptual Typology of Moisture Recycling Exchange among Countries



Source: Keys et al. 2017.

richer countries are reluctant to accept financial responsibility for the impacts of their climate-related actions on more vulnerable countries (Bhandari et al. 2022).[12]

Both the Amazon and Congo Basins represent Type 3 networks of moisture exchange, where Type 3 represents a combination of Type 1 and Type 2. In both cases, there is one country that controls the majority of the tropical forest precipitationshed. However, both basins also have some Type 4 characteristics, whereby it is not a simple exercise to link a specific harm to a few causes (Keys et al. 2017), complicating the design of any prospective PES scheme. Additionally, the lack of institutions currently in place to mediate among potentially divergent interests means that relevant countries will need new norms and principles to establish shared expectations and standards of behavior related to regional TMR. The strengthening or creation of transboundary governance institutions and agreements may also be required, potentially including the use of financial and economic incentive instruments (Keys et al. 2017). Such measures are the focus of this section.

Raising Awareness and Establishing Norms

Current global governance mechanisms for transboundary air, water, and forest management have set useful cooperation principles and norms for transboundary water management, but as mentioned above, so far have neglected TMR. Setting specific norms for atmospheric water that would cover all three governance spheres would help to set shared expectations and standards of behaviors by organizations across the three governance spheres of atmosphere, water, and forests, and could clarify operating principles that have resulted in confusion for current international conventions (Ellison et al. 2018). For example, there has been much debate over how to balance and prioritize among the principles of "equitable and reasonable utilization" and "do no harm" reflected in the 1997 UN Watercourses Convention, and there is a lack of guidance as to how climate considerations should be integrated into these concepts (Sanchez and Roberts 2014). Establishing norms may be a good first step to help guide regions in the other illustrative cases below. Box 4.3 describes the example provided by the World Commission on Dams.

BOX 4.3 | Multistakeholder Norm-Setting: The World Commission on Dams

The World Commission on Dams (WCD) provides a useful analogue as a multistakeholder norm-setting initiative that has high relevance for addressing deforestation's impact on regional precipitation. Established in 1998 in response to growing concerns over the influence of international financial institutions in the construction of large dams, the commission functioned to review the development effectiveness of dams and to develop global standards and guidelines that incorporated knowledge of the environmental, social, and economic impacts of the development of large dams globally.[a] Its governance structure comprised 12 commissioners representing diverse points of view on dams, a consultative forum, and a secretariat. The commission had a two-year research and deliberation period that culminated in a recommended framework for the decision-making process around dams.[b]

The commission has largely been considered successful, especially for its ability to reframe the issue of dam construction to have more of a human rights focus.[b] An assessment of the commission's history, accomplishments, and lessons learned highlighted four good governance principles adopted by the WCD that could be applicable to transboundary norm-setting bodies addressing TMR. The principles included representation of all stakeholder groups, independence from external influence, transparency in knowledge-gathering and decision-making processes, and a robust and inclusive process that allowed for diverse viewpoints to be represented in the commission's work.[c]

Sources: a. International Rivers 2008; b. Martinsson 2011; c. Dubash et al. 2001.

While norms can be established through various routes such as through legal means or multistakeholder initiatives, the latter is perhaps the most relevant route, given the importance of both state and nonstate actors for forest and water management. Norm-setting bodies could focus on four major objectives:

1. Bringing attention to how land-use changes affect regional precipitation patterns and recognizing TMR as an important ecosystem service that is of high significance for regional water balances. Such raised awareness could encourage expansion of transboundary water governance beyond traditional scales (e.g., river basin or watershed) to include precipitationsheds and evaporationsheds.
2. Establishing (and clarifying) principles for how interstate actors and already established water governance bodies can work together and extend such collaboration to forest and atmospheric management institutions. Such processes could build on existing principles established through UN conventions (e.g., precautionary principle, accountability, transparency, participatory approach, avoidance of harm, conflict resolution, etc.), with a greater focus on sustainable development, ecosystem services, and climate change mitigation and adaptation.
3. Recommending a framework for decision-making processes around land-use change that is likely to affect transboundary precipitation.
4. Recommending research priorities for reducing uncertainties in the science of attributing specific land-use changes to specific impacts, as well as estimating associated economic harm.

Adapting Existing Institutions to Address TMR

Several experts have suggested that policymakers consider precipitation as a resource base to be managed in addition to surface and groundwater, and for consideration of precipitationsheds and evaporationsheds instead of or in addition to traditional water basins (Ellison et al. 2018; Keys et al. 2017). The need for new institutions depends on the strength of existing institutions and their ability to take on consideration of TMR issues. Given the high number of existing institutions and actors operating on transboundary air, water, and forest management challenges, it is worth considering how existing institutions could be adapted to accommodate TMR.

While taking account of the significant challenges and limitations noted above, transboundary river basin treaties offer a place to start. According to Keys et al. (2017), “Given the overlap in territorial coverage, the evolution of treaty objectives, and the multilateral character of many treaties, recognizing moisture recycling flows within transboundary river basin treaties could prove to be a viable way to govern precipitationsheds.” Determining how best to adapt these treaties to address TMR will of course depend on the regional context, but as a point of departure some generalizable modifications might include the following:

- Recognition of the entire precipitationshed and evaporationshed area, and consideration of the extent to which it overlaps with the current area governed by the treaty. Such an analysis would support stakeholder mapping to identify additional state and nonstate actors, including upwind and downwind governments and nonstate actors involved with land-use and water management (e.g., forest managers, Indigenous communities, watershed committees, agricultural producers' groups) that would either need to be included as parties to agreements or as participants in multistakeholder processes.
- Recognition of TMR as a vital ecosystem service and integration of land use into water resources planning frameworks, perhaps by changing from an integrated water resources management (IWRM) framework to an integrated land and water resources management framework (Keys et al. 2017).
- Promotion of the aforementioned norms and principles that better align with TMR.

In the Amazon Basin region, the 1978 Amazon Cooperation Treaty (ACT), signed by Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, and Venezuela, governs the river basin. The ACT was established to foster the sustainable development of the Amazon River Basin. The 1998 Amendment to the ACT established the Amazon Cooperation Treaty Organization (ACTO). In 2005, the ACTO worked with the Global Environment Facility (GEF) and others to launch the "GEF Amazonas Project," which sought to integrate climate change considerations and greater public participation into the sustainable development of the river (International Waters Governance 2020). Adapting the ACT for TMR would require the inclusion of missing countries from the moisture flow regime, including Paraguay, Uruguay, and Argentina.

Similar challenges related to the scope of current membership would adhere to addressing TMR through regional institutions focused on forest-related cooperation. For example, the Leticia Pact for the Amazon Region was signed by Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, and Suriname in 2019 in the aftermath of catastrophic forest fires. The pact includes commitments by member states to collaborate on several objectives of relevance to TMR, including disaster prevention and management, and to "improve the monitoring capabilities of climate, biodiversity, water, and hydrobiological resources of the region under a watershed approach" (Morales Ayma et al. 2019). The pact has been complemented with an action plan and seed funding from the Inter-American Development Bank ("Action Plan" 2019). While the pact calls on "other interested States" to cooperate, its membership does not include downwind countries in the region affected by TMR.

In the Congo Basin region, the Central African Forest Commission (COMIFAC) was established in 2005 under a treaty on the conservation of sustainable management of forest ecosystems. Its membership includes Burundi, Cameroon, Central African Republic, Chad, Democratic Republic of Congo, Gabon, Equatorial Guinea, Rwanda, and São Tomé and Principe (COMIFAC 2005). COMIFAC is complemented by the Congo Basin Forest Partnership (CBFP), a voluntary multistakeholder initiative including donor countries, civil society organizations, and private sector actors, to attract and coordinate financial and technical support for the region's forests (UN 2002). While the memberships and mandates of COMIFAC and the CBFP are appropriate vehicles for raising awareness and advocating for more such support based on the importance of TMR, their memberships do not include interested states across the continent affected by TMR. Box 4.4 describes various World Bank initiatives, including support for the Nile Basin Initiative, that might provide relevant precedents for the involvement of multilateral development banks in support of this agenda.

BOX 4.4 | A Role for Multilateral Development Banks?

As suggested in the story that opened this chapter, multilateral development banks might have a role to play in advancing some of the policy directions described in this section to advance regional cooperation on TMR among developing countries. The World Bank provides several precedents.

Since 2011, the World Bank has managed the Cooperation in International Waters in Africa Program with the objective of "addressing constraints to cooperative management and development in transboundary waters."[a] One of the program's partners is the Nile Basin Initiative, an international partnership among 10 Nile Basin countries. A series of projects supported by the program has focused on climate resilience, especially flood and drought forecasting and risk mitigation in the Nile Basin. Although the project, which is supported by a multidonor trust fund, does not address TMR, several of the functions of the program—that is, providing information and investment and building institutions—map to the needs identified for cooperation to confront the risk of changing rainfall patterns due to deforestation in precipitationsheds.[b]

The World Bank also served as an observer and provided technical input to negotiations brokered by the United States among the governments of Egypt, Ethiopia, and Sudan in 2020, regarding the filling and operation of the Grand Ethiopian Renaissance Dam.[c] Egypt has feared that the dam threatens its water supply from the Nile River, while Ethiopia has resisted giving up water rights.[d] Although the dam was filled in mid-2021, and recent modeling research indicates that regional cooperation in its operations would increase economic benefits,[e] agreement among the countries has remained elusive.

Of particular relevance to TMR, in 2019 the World Bank–managed Program on Forests (PROFOR, another multidonor trust fund concluded in 2020) launched a project to improve understanding of forest-water interactions among the World Bank's project teams and partners working in the Congo Basin. The initiative sought to identify links between forest loss and degradation and water resources in the Congo Basin, covering local and regional hydrological impacts—including via atmospheric moisture flows. The research found that deforestation in the Congo Basin not only effects the region itself but also Africa as a whole and the rest of the world.[f] While the project has concluded, it produced an interactive e-book and associated data and knowledge portals to help disseminate the findings and create an evidence base for World Bank staff working in the region.[g]

Sources: a. World Bank 2022; b. Tanaka 2021; c. U.S. Department of the Treasury 2020; d. Widakuswara 2020; e. Basheer et al. 2021; f. PROFOR 2020; g. World Bank 2019.

Addressing Uncertainty

Whether to serve as a basis for any new institution or for revisions to existing institutions, there is also a need to build more scientific certainty regarding TMR pathways and to set forth clear deforestation thresholds and priorities for addressing land-use change. Meeting this objective requires strengthening the understanding and modeling of TMR, especially in the Congo Basin and nontropical forest areas. The literature also suggests improving monitoring of forest-water outcomes, spatial planning, ecosystem service valuation, and impact assessments as key tools for informing regulatory instruments and governance institutions (Ellison et al. 2018; Te Wierik et al. 2021). Monitoring of land-use change and resultant changes in local and regional water quantity is needed to calibrate models and improve our understanding of forest-water-atmosphere connections.

Spatial planning involves the identification of priority areas for protection and restoration based on an understanding of precipitationsheds and evaporationsheds and moisture recycling trajectories. Economic valuation of costs and benefits of TMR-focused policies and investments as well as impact assessments that quantify job, income, and multiplier effect outcomes would allow decision-makers to better understand which stakeholders are most at risk and which stakeholders stand to gain from changes in TMR. It is important that economic valuation and impact studies disaggregate costs, benefits, and impacts by relevant demographic groups as well as geographies to develop the most appropriate policies and financing mechanisms. To date, there has been limited assessment of the social, economic, and ecological vulnerabilities associated with TMR (Bagley et al. 2012; Keys et al. 2012, 2018). The authors are not aware of quantification or detailed analysis of the regional economic, social, and environmental impacts and economic costs and benefits related to TMR.

The UNECE Convention on Long-Range Transboundary Air Pollution (the "Air Convention") provides a useful policy analogue in this regard (Ellison et al. 2018). The Air Convention and its eight protocols have been hailed as a success story for their ability to convene countries to tackle the transboundary acid rain problem across Europe, the United States, and Canada. The convention has resulted in emissions reductions for all targeted air pollutants, with sulfur dioxide emissions in Europe being reduced by 80 percent from peak levels (Greenfelt et al. 2020).

The Air Convention has been especially effective in strengthening the science around the causes and pathways of air pollution (Ellison et al. 2018). The convention requires each party to undertake monitoring, modeling, and data collection of atmospheric concentrations and deposition, as well as long-term field experiments to study acid rain's impacts on ecosystems. The convention successfully connected scientific findings to policy approaches by quantifying the transboundary fluxes of pollutants and establishing critical thresholds, so that it was clear which country needed to cut back on which pollutants, and who would benefit from those reductions. Similar to the World Commission on Dams, the Air Convention also prioritized transparency in data as a key principle, which has helped to reduce concerns regarding the utility of atmospheric modeling as a driver of priority-setting (Greenfelt et al. 2020).

Having similar regional conventions or monitoring and scientific bodies for TMR could help to build confidence in atmospheric water modeling and identify appropriate methods for modeling and analysis of TMR pathways and impacts. Such a scientific basis could enable policymakers and other stakeholders to more clearly delineate responsibility for and impacts from deforestation from one or a set of countries, to clarify the deforestation-related tipping points that would need to be avoided, and to better connect the science on local vs. regional impacts of forest loss to ensure that the interests of local actors are taken into account along with those of downwind actors. It should be noted, however, that unlike air pollution, TMR presents unique complications with identifying point sources, given the diffuse character of impacts of deforestation on rates of evapotranspiration.

In order to generate faster policy responses to the impacts of land-use change on TMR, it may be necessary to enlist the functions of additional institutions. Specifically, meteorological organizations may be best equipped (compared to land or water management agencies) to monitor rainfall and detect changes. To play this role at a regional transboundary scale, national weather monitoring systems would need to be coordinated across countries constituting the relevant precipitationshed and evaporationsheds.

Utilizing Financial Instruments

Economic or market incentive policies are especially useful for dealing with environmental problems that span administrative borders. Such policies have been well vetted through domestic policy innovations within various national contexts. Cap-and-trade schemes have been used to address acid rain and reduction of GHG emissions; payments for ecosystem services (PES) have been used widely in developing and developed countries, especially for water provision as the targeted ecosystem service (Grima et al. 2016).

PES has direct relevance for regional TMR, although it presents unique complexities compared to other ecosystem service types and programs that operate at the local or catchment scale. Successful PES schemes generally have a well-defined ecosystem service, geographic boundaries, users/beneficiaries, and providers (Fripp 2014). Additionally, having clearly defined property rights and strong community engagement have been key success factors for PES schemes in Mexico and Costa Rica (Min-Venditti et al. 2017). A PES scheme for TMR would thus need careful modeling to properly identify these elements and address ecosystem service provision measurement challenges. But as TMR is an ecosystem service with potentially identifiable sources and sinks of precipitation, PES could offer a policy mechanism with high potential to improve forest management, conservation, and restoration in targeted precipitationsheds such as the Amazon and Congo Basins.

Latin America has in fact been a pioneer of PES. In a review of 50 PES schemes in Latin America, Grima et al. (2016) found that over half of the schemes focused on water as the key ecosystem service, and 12 percent focused on landscape protection. Increasing water shortages and water pollution issues, especially those affecting urban areas, have been the most important motivations for PES schemes in Latin America (Grima et al. 2016). However, most PES schemes have been implemented at the subnational scale and are largely focused on specific watersheds.

A network of Water Funds in Latin America provides useful experience for understanding how regional PES schemes that focus on paying for forest restoration and sustainable management in precipitationsheds financed by those in evaporationsheds could work (Latin American Water Funds Partnership n.d.). The Water Funds, pioneered by the city of Quito, "design and promote financial and governance mechanisms, engaging public, private and civil society stakeholders in order to contribute to water security through solutions grounded on nature-based infrastructure and sustainable management of watersheds" (Latin American Water Funds Partnership n.d.).

However, regional-scale PES would likely experience traditional challenges to PES to a higher degree, such as high up-front costs and associated financing barriers, technical implementation issues, and lack of trust among diverse stakeholders. To promote the establishment of a PES scheme for TMR, strong political support would likely be needed to create a positive enabling environment through supporting legislation or institutions to address these problems. To remedy the trust issue, PES schemes could tap into any positive shared history of collaboration between countries, especially existing transboundary water management organizations, and also build confidence in the scientific basis for collaboration through improved monitoring, as described above.

The PES policy option raises the question of how such a scheme would be financed. As mentioned above, although the agriculture sector faces profound risks from rainfall disruptions due to deforestation, poor countries and poor farmers are not a viable source of finance. In such cases, international public finance may be necessary. In other cases, however, there might be willingness and ability to pay by various stakeholders in downwind countries.

For example, given that so many cities in Latin America are facing water shortages due to severe drought, flooding, and water pollution problems, urban beneficiaries of precipitation might be willing to fund upwind forest restoration, conservation, and management efforts. Ozment et al. (2018) estimated the return on investment of potential watershed restoration strategies for the Cantereira water supply system in São Paulo, Brazil. The study focuses on sediment reduction benefits from improvements to the immediate watershed supplying water to São Paulo and highlights that forests can provide a multitude of cobenefits. These cobenefits could be used to promote a regional-scale PES scheme.

Another vital funding source will be the private sector. There is significant need for catalytic capital to de-risk forest investments and leverage public sector financing. Recent research (Cooper and Tremolet 2019; Gray 2022; UNEP 2021) has highlighted the need for and growth in innovative finance mechanisms such as green bonds, blended finance, guarantees, and insurance products to support forest conservation and restoration, and more broadly, "nature-based solutions" (NbS) to problems related to climate mitigation and adaptation. Multilateral development banks and other development finance institutions have a critical role to play in building trust in NbS by supporting the creation of enabling conditions and preparing projects that are ready for private finance. By taking a regional approach to TMR management, such public institutions could collaborate with private investors to build portfolios of investments that help connect the dots between forest protection in precipitationsheds and the benefits of such protection in evaporationsheds.

CONCLUSIONS

The preceding analysis suggests several policy directions for managing the risks of disruptions to rainfall at the regional scale caused by deforestation in upwind countries.

First, there is significant scope for investment in further development of the data and analysis of TMR in specific regions to reduce uncertainty regarding the magnitude of the effects of forest loss on rainfall and the downwind areas most likely to be at risk. The results of such analysis could be used to raise awareness among key stakeholders—forest managers in precipitationsheds, and farmers, agribusiness interests, and urban leaders in evaporationsheds—as well as policymakers in national governments and international institutions, that TMR is a vital ecosystem service that needs to be managed.

Second, transboundary water management bodies, such as river basin authorities, provide opportunities to build on existing institutions with relevant mandates and memberships. While the governing effectiveness of such institutions has been mixed, their experiences, and that of policy analogues such as the UNECE Air Convention, point to specific attributes and functions that can help improve their effectiveness. Such attributes include agreement on principles and norms, inclusive membership, transparency of process, and investment in rigorous monitoring and reporting.

Third, due to the economic value of rainfall to downwind countries, and especially risks to food and water security, the potential for developing transboundary PES schemes and innovative finance mechanisms to support forest protection in upwind countries could be explored. While the political and institutional challenges are daunting, and the feasibility of implementation questionable, discussion of the possibility of such schemes could at minimum serve to raise awareness of the downwind economic impacts at stake. Experience with PES schemes at the scale of individual watersheds provides a base of experience to build on.

Finally, when the relevant countries are in developing regions—as is the case for the areas affected by deforestation in both the Amazon Basin and the Congo Basin—multilateral development banks may have a role in supporting regional cooperation on TMR in light of their ability to support information generation and sharing as well as to provide finance. Additionally, the growing body of evidence on innovative NbS finance mechanisms is providing useful information to structure new financing approaches that include both public and private sector funders.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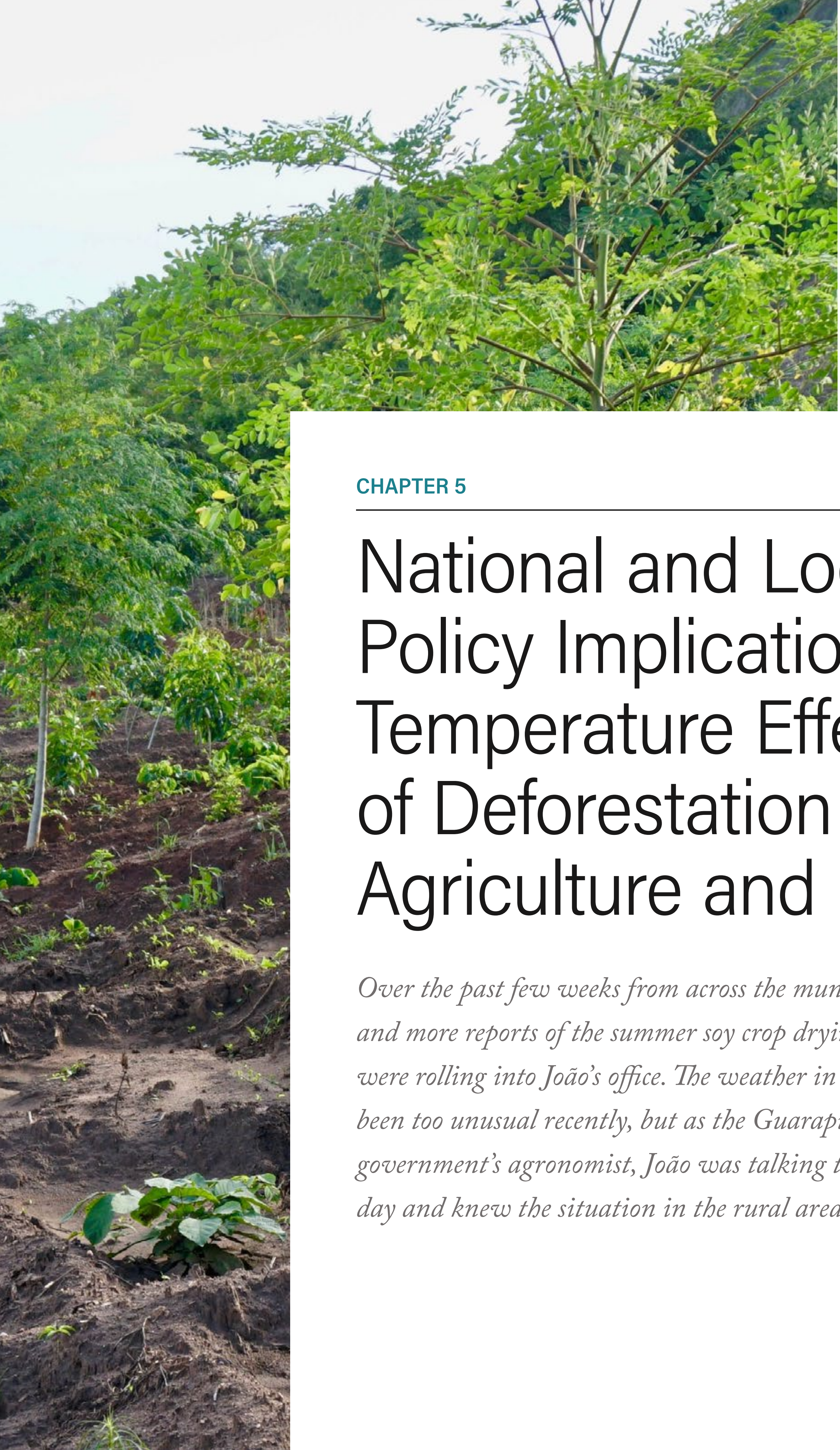


CHAPTER 5

National and Local Policy Implications: Temperature Effects of Deforestation on Agriculture and Health

Over the past few weeks from across the municipality, more and more reports of the summer soy crop drying in the fields were rolling into João's office. The weather in town hadn't been too unusual recently, but as the Guarapuava municipal government's agronomist, João was talking to farmers every day and knew the situation in the rural areas was different.

After a drier than usual winter left much of the area's maize crop wilting on the stalks back in August, the year's soy crop started out the early season well. The rains had worked in his farmers' favor—just the right amounts in early September to get their seeds in the ground and off to a good start before the heavy October rains.

But now, in February, when the soy plants should be shifting their energy from growing leaves to fattening their protein- and oil-rich beans, they were starting to wilt on the vine on farm after farm across town.

João called up his former classmate from UFRGS (the Federal University of Rio Grande do Sul), who had also made her way to Paraná in the agricultural boom of the past two decades and was now the chief agronomist for the state, stationed in Curitiba. They talked about the changes they had both seen in the area. In just 20 years, the land had changed from a frontier wildland dotted with farms, to farmland dotted with silos, barns, and a few scrubby patches of woods.

"The climate is changing, Fernanda," he said. "Even the skilled farmers are struggling more and more, even though they followed the maps and rules and planting schedules." "The weather stations are showing more warming in the fields than in the cities, amigo. I've been reading some new research that suggests it might be an impact from clearing too much Cerrado—the forests and scrub used to keep the surrounding land cooler," Fernanda replied. "But if our farmers can't clear more Cerrado, how can we keep our economy going?" João asked. "We need to find a different way."

This imagined story is based loosely on Paraná's and Guarapuava's history of natural ecosystem conversion over the past few decades, its extensive reliance on rainfed double-cropping systems, data on the area's rainfall patterns and typical planting dates, and new scientific research linking rainfall in the region to ecosystem loss in the Amazon and Cerrado.

Suhartini adjusted her headscarf, damp from perspiration under the scorching sun. The oil palms in this newer section of the plantation in Kalimantan (Indonesian Borneo) were too young to provide shade. Her hands were stinging from the fertilizer she was tossing at the base of each trunk. Workers were supposed to wear protective gear, but the gloves provided by the company were ill-fitting and slowed her down.

The doctor at the clinic had told her to avoid handling pesticide sprayers when she was pregnant with her last child, but sometimes that was the only work available for casual laborers. It was the same doctor who had treated her for a persistent cough after the heavy smoke from the extensive land fires in 2015, and it was the same clinic that was now struggling to handle a surge of patients during the COVID-19 pandemic.

Most days, she accompanied her husband Arief to his job harvesting bunches of oil palm fruit from stands in the older parts of the plantation, which had expanded several kilometers into the forest since the bulldozers first arrived 15 years earlier. She helped him meet his quota by pushing the wheelbarrow and gathering up stray oilseeds while he wielded the heavy sickle, a sharp curved knife mounted on a long wooden pole, to free fruit bunches high overhead.

She was increasingly worried about the effects of the ever-increasing midday heat on Arief's ability to work effectively and think straight. It seemed that he was taking more frequent and longer breaks, meaning he was increasingly dependent on her help to meet his quota. He seemed to be getting clumsier with the sickle, risking an accident with its sharp steel blade. And most worrying, he sometimes seemed confused *at the end of the shift in the early afternoon—more than once he had allowed himself to be shortchanged on the pay he was owed based on the weight of his harvest—and that was money they needed to pay the fees at the clinic.*

This imagined story is loosely based on research findings by a Center for International Forestry Research (CIFOR) team led by Bimbika Sijapati-Basnett (see, e.g., "Gender and Oil Palm," CIFOR *Forests News*, 2017) and the findings of studies in Berau District of East Kalimantan conducted by a research team supported by The Nature Conservancy, including Masuda et al. (2020, 2022).

Scientific understanding of local forest-atmosphere interactions has advanced significantly in the last decade. The recently released synthesis by Lawrence et al. (2022) shows that temperatures increase significantly where deforestation has taken place and in nearby areas, and rainfall shifts tend toward drying.

Chapters 3 and 4 touched on some of these more local impacts as they relate to global and regional policy contexts. This chapter analyzes the gaps in policies and institutions that must be filled to address the biophysical roles of forests in stabilizing the climate at local scales, with **a focus on temperature effects on agricultural productivity and human health in the tropics**. (Box 5.1 briefly complements Chapter 4's focus on the effects of deforestation on rainfall and describes the implications for double cropping in Brazil.)

We begin with a brief summary of the science on biophysical forest-climate effects related to local climate changes—including recent advances—that are relevant to national and local policy, with an emphasis on temperature effects, to avoid excessive overlap with Chapter 4's focus on precipitation effects. We then examine two specific case studies: soy productivity in Brazil and human heat stress in Indonesia. In each case, we extend from the science on local forest-climate interactions, to emerging science related to impacts. We seek to identify potential policy venues and contexts where policymakers could give additional consideration to these local climate impacts of forest cover change.

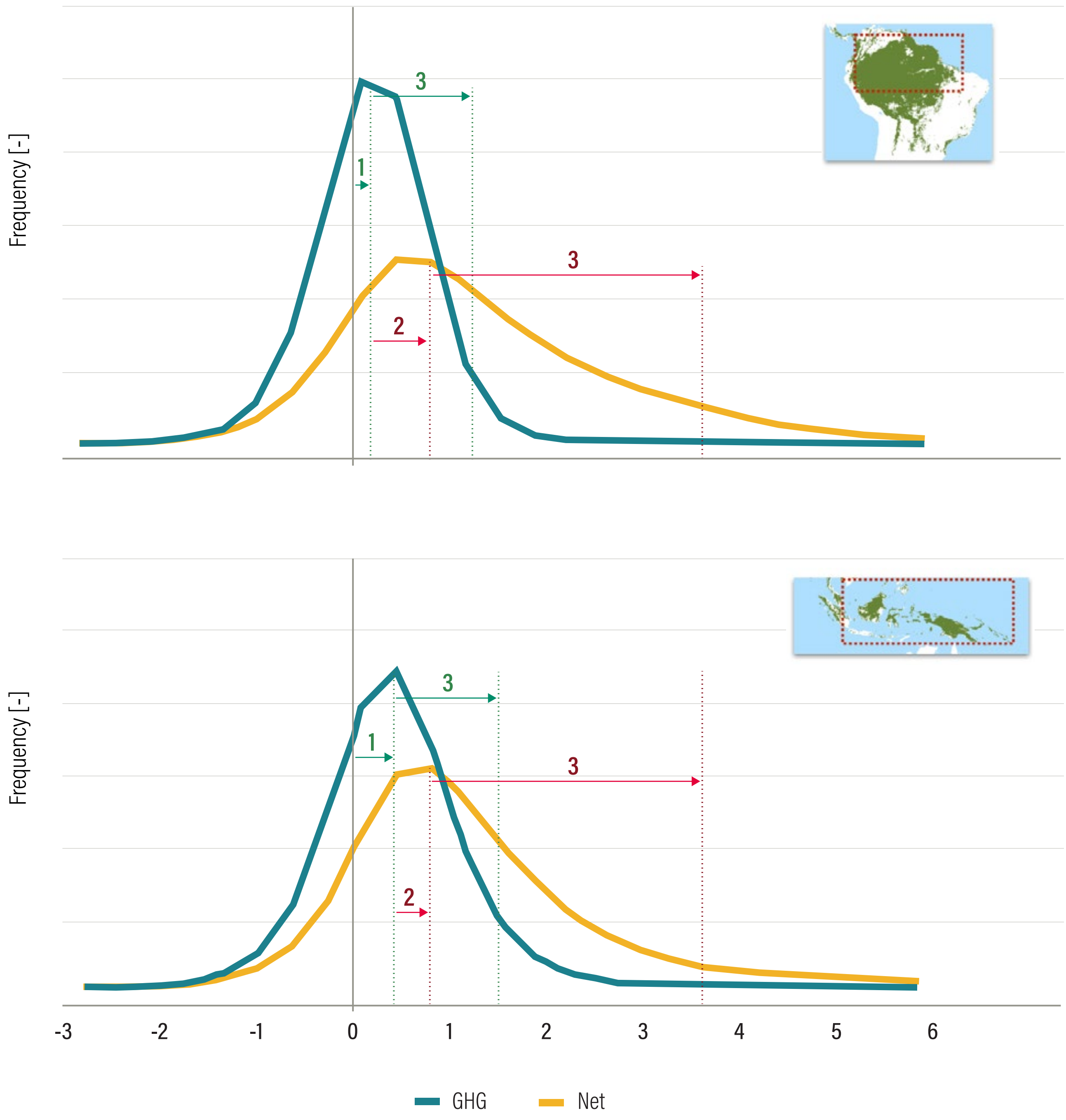
SCIENCE OVERVIEW

Tree cover (and its loss) have much bigger effects on local climate through biophysical processes including evapotranspiration, albedo, and surface roughness than through global GHG effects (see Chapter 2; Ellison et al. 2017; Bright et al. 2017; and Lawrence et al. 2022, Figure 5). Biophysical impacts also happen immediately when forests are lost, rather than slowly over decades as in the case of GHG-caused warming.

In the tropics, local temperature changes in response to forest loss can be extreme—a synthesis of observational data shows annual average surface temperatures are 0.2°–2.4°C cooler in forests than in cleared areas nearby (mean 0.96°C, Lawrence et al. 2022, Figure 1), with greater differences during the hottest parts of the day and the hottest parts of the year. Some field-based estimates indicate average temperature differences as high as 8.3°C between forested and deforested areas (Masuda et al. 2019). Temperature changes are more extreme within the largest patches of deforestation (Vargas Zeppetello et al. 2020), where there has been more nearby (within 5 km) deforestation (Prevedello et al. 2019) and even where forests remain but there has been more degradation (Longo et al. 2020). Temperature changes from lost forest cover have been more extreme in the Amazon than in the Congo Basin or Southeast Asia but are observed across all three tropical forest zones (Vargas Zeppetello et al. 2020). Forests have similar local and regional impacts on moisture availability—including rainfall, soil moisture, and the ability of plants to use available water (see Chapters 2 and 4). Forests also buffer *extremes* of both temperature and rainfall, reducing variability—which provides significant economic value beyond moderating averages (Calel et al. 2020).

Observed temperature changes in the Amazon and in Indonesia show these effects clearly (Figure 5.1, adapted from Vargas Zeppetello et al. 2020). Areas that maintained forest cover from 2003 to 2018 saw some moderate increase in average temperatures, in line with the global warming over the period (Figure 5.1, arrows labeled 1). In comparison, areas that lost forest saw larger increases in average temperatures (Figure 5.1, arrows labeled 2). But the temperature variability and skew were also much higher in areas that lost forest—for example in the Amazon where 12 percent of deforested areas saw temperature increases

FIGURE 5.1 | Tropical Deforestation Increases Local Average Temperature and Variability



Notes: Frequency distributions of the change in annual average daytime temperature between 2003 and 2018 for grid cells that kept their forest cover, and those where deforestation occurred, with 2003 forest cover in study regions represented in the insets. Arrows added by authors as referenced in text.

Source: Modified from Vargas Zeppetello et al. 2020.

of more than 3°C, while fewer than 1 percent of areas that maintained forest cover saw temperature increases this extreme (Figure 5.1, arrows labeled 3 representing approximately two standard deviation increases in temperature).

It is important to note that deforestation's effects on temperature and on moisture recycling are closely intertwined. When temperatures are higher, the same amount of rainfall is less useful to plants: more of that rainfall evaporates before the plants can absorb it, and they use up the water they do absorb more quickly through faster transpiration. But this also goes the other way: the same high temperatures will damage plants more if there is less rain or irrigation in a field. The evidence of deforestation's impact on agriculture does not always disentangle the temperature effects from rainfall and/or moisture effects (e.g., Spera et al. 2020; Barkhordarian et al. 2019). Perhaps more important from the perspective of this analysis is that the risks from simultaneous impacts across multiple processes are often compounded (Zscheischler et al. 2018)—in other words, when the local temperature goes up (as we discuss in this chapter) AND moisture recycling is disrupted (as we discuss in Chapter 4), the risks and impacts can multiply rather than add.

While we focus in this chapter on national and subnational policy contexts to potentially address deforestation's temperature-mediated impacts, first on soy productivity in Brazil and then on human health in palm-producing regions of Indonesia, we note that the potential policy venues for addressing deforestation's moisture mediating impacts at these scales are likely similar.

AGRICULTURAL PRODUCTIVITY, TEMPERATURE, AND DEFORESTATION

Linking Deforestation Heat Stress to Crop Productivity

Decades of research on the relationship between climate and crop productivity have shown a close link between temperature, rainfall, and their variability and extremes, on the one hand, and global and regional agricultural productivity, on the other—especially the impacts of extremes in the tropics and in drier regions (Matiu et al. 2017). Changes need not be extreme to have a negative impact: when crops are already near the upper bounds of their preferred climate envelope, a small change in averages can result in large increases in the number of extreme days with significant impacts on yields (Zilli et al. 2020).

When put together, the independent lines of evidence that agricultural productivity can decline in the face of temperature increases and extremes, and that forest loss in the tropics leads to increasing local temperatures and extremes through biophysical pathways, strongly suggest that agricultural areas near deforested land have and will continue to experience temperature-related productivity declines. Plants don't care if heat stress is a result of a changing global climate, changing local climate, or even just a particularly hot summer within the range of normal variability—productivity can decline regardless.

Both of these processes—increasing temperatures and extremes associated with forest loss, and decreasing yields associated with increasing temperatures—have been well-documented with respect to Brazil and with respect to soy. For example, Alkama and Cescatti (2016) observe agricultural areas in Brazil with daily maximum near-surface temperatures as much as 4°C hotter than expected without deforestation. Cohn et al. (2019) find a signal of increased maximum daily temperature up to 50 km away from deforestation in the Brazilian Amazon and Cerrado—with a 25 percent increase in clearing leading to about 0.75°C increase in daily maximum temperatures. Observed soy yields begin to decrease rapidly with the number of days above 30°C (Schlenker and Roberts 2009).

A newly published study by Flach et al. (2021) combines these two lines of evidence to estimate the temperature impacts of nearby deforestation on soy yields and incomes in Brazil. The authors estimate that the value of forest biophysical cooling lost in 2012 from recent land conversion (1985–2012) was over $158 per hectare per year in the Amazon and $85 in the Cerrado (as measured in 2005 US$) from productivity losses of about 12 and 6 percent, respectively. In future scenarios, with additional agricultural expansion, temperature and soy price increases, and further deforestation-driven biophysical warming combined with additional global biogeochemical (GHG-based) warming, they expect the value of heat regulation from forest conservation to increase significantly—25 to 95 percent, depending on the scenario.

While these local temperature effects will certainly affect the productivity of commercial-scale agricultural enterprises, they will also amplify the risks already faced by Indigenous Peoples and local communities due to global climate change. The risks associated with the loss of ecosystem services include malnutrition due to decreases in food production, access to food, and diversity of diets, and the inability to meet basic needs that depend on those services (IPCC 2022).

BOX 5.1 | Double Cropping, Rainfall, and Deforestation in Brazil

A significant component of Brazil's recent rise as a global agricultural powerhouse has been the expansion of *double cropping*—growing two full crops per year on the same land).[a] Most double cropping in Brazil is rainfed soy-maize rotations and depends on getting enough rain at the right times of both growing seasons.[b] Much of the region's rainfall depends on upwind forests through terrestrial moisture recycling (see Chapter 4), and basin-wide deforestation is already threatening that rainfall[c] and expected to get worse in the coming decades (Costa et al. 2019). New research is providing evidence that rainfall declines are not just a regional process, but also happen at much more local scales when forest loss is significant.[d] The more local the area, the more extreme forest cover loss has to be before rainfall decreases—over about 60 percent loss in 28 km x 28 km grid cells, 50 percent in 56 km cells, and 30 percent in 112 km cells. Beyond an area 224 km on the side, any amount of forest loss is associated with rainfall declines. For reference, the Brazilian state of Mato Grosso is about 1,000 km across, while tree cover and primary forest cover loss in the state both total about 21 percent from 2001 to 2020[e]—and more if one looks over longer periods of time. The Matopiba region—a region with significant soy production and deforestation—is more than 1,000 km from any national border. These facts suggest that risks to Brazil's soy industry from deforestation are a significant domestic (as well as regional) issue and need to be addressed in domestic policy contexts as well as in the types of regional policy contexts discussed in Chapter 4.

Sources: a. Elwin and Baldock 2021; b. Abrahão and Costa 2018; c. O'Connor et al. 2021b; d. Leite-Filho et al. 2021; e. GFW 2020.

The process whereby forest cover loss increases temperatures with negative impacts on agriculture may work in the other direction as well: introducing trees into agricultural lands through agro-forestry systems have been shown across Latin America and Africa to buffer crops from temperature extremes and increase crop resilience to both local biophysically driven and global GHG-driven climate changes (see, e.g., Chemura et al. 2021; Vargas Zeppetello et al. 2022).

Deforestation, Temperature, and Agriculture: National and Local Policy Opportunities

The evidence that deforestation-driven temperature increases already have had significant negative impacts on soybean productivity in Brazil, and that these impacts will increase in the future, should lead national and local agriculture policymakers to bring consideration of agricultural impacts from deforestation into their decision-making. We maintain our focus on the example of Brazil and look to where there is already an active policy process considering climate-related agricultural risks in the context of climate change writ large.

Soy production in Brazil has exploded in the last few decades from less than a million tons in 1961 (Ritchie and Roser 2021) to now being the largest global production at over 137 million tons in the 2020–21 growing year (USDA 2021a), with further growth expected. This expansion was driven in part by breeding and genetic modifications that allowed soy to grow in tropical climates (Flach et al. 2021). But it came at the cost of forests and other natural ecosystems. Soy production area in the Brazilian Amazon increased more than tenfold from 2000 to 2019, to 4.6 million hectares, and while most of that increase came at the cost of pasture in the short term, nearly half of the Amazon region's soy production area in 2019 had been forest in 2001 (Song et al. 2021). Further expansion risks killing the goose that lays the golden egg.

Although the negative feedback loop between deforestation and soy production is particularly pronounced in Brazil, similar climate risks may also be happening on a smaller scale for other crops in other geographies. For example, in Côte d'Ivoire and Ghana, local deforestation impacts on temperature are clearly being observed (Alkama and Cescatti 2016). In these countries cocoa expansion is driving deforestation at the same time smallholder cocoa farmers are experiencing climate stresses, and long-term climate trends are likely to drive decreases in the area suitable for cocoa, mostly as a result of rainfall changes (Kroeger et al. 2017).

There are already several well-developed policy venues and contexts that are considering the climate-forest-agriculture nexus across national, state, and municipality levels of government in Brazil. Most policy work at this nexus in Brazil has focused on agriculture as a driver of global warming through the carbon emissions that happen when forests are cleared. In this story line, the "bad outcomes" and source of concern are the global climate impacts that result from deforestation. But when it comes to the local climate effects of deforestation, the "bad outcomes" hit individual farmers and the agriculture sector directly, not mediated through global climate change. This process—deforestation causing changes that negatively impact agriculture, rather than agricultural expansion causing forest cover changes and subsequently global warming—has not been a major driver of policymaking in Brazil. Largely, the conventional wisdom remains that production is increased via expansion into forest frontiers. And while this may be true for an individual farmer at the forest frontier, the evidence is increasing that Brazil may soon reach tipping points where the soy industry as a whole could experience productivity *declines* from continued area expansion.

Whatever the direction of impact (agriculture on tree cover, or tree cover on agriculture), the most critical change needed on the ground is the same: slowing and reversing agriculture-driven deforestation. The policy solutions—and thus the relevant policy contexts and forums—are largely the same as well. What shifts are the incentives for action by different stakeholders and, potentially as a result, the political economy factors that can block or accelerate solutions. We briefly describe three specific and closely related policy contexts where the risks to agricultural productivity from deforestation-driven temperature increases could be addressed. A complementary, private sector–led approach not further explored here could be the integration of deforestation-related climate risk into the availability and cost of insurance coverage for agricultural investments.

National REDD+

Brazil has more than two decades of history trying to control forest loss in the Amazon and Cerrado biomes through agriculture-related policy at multiple levels of government. These include, for example, the National REDD+ strategy, the Amazon Fund and BNDES rural credit programs, the Forest Code and its implementation, Brazil's climate emissions targets and planning, among others (Stabile et al. 2020).

In the context of agriculture *driving* deforestation, and concerns about the climate impacts thereof, the role of agriculture sector actors has been politically unstable and fraught. They are largely approached as the actors needing regulation and external incentives. Partly as a result of these politics and perceptions, progress on REDD+ in Brazil has experienced waves of progress followed by reactionary backtracking.

But with clear science linking forest loss to *present* agricultural productivity declines from local biophysical heating at the order of several degrees—not just *future* declines from global GHG warming—it is the same actor group that is feeling the impacts as is causing them. If the policy contexts addressing REDD+ are able to incorporate additional consideration of biophysical processes and their impacts on farmers, there may be some potential to shift the political balance toward broader support for REDD+, including at least some agricultural constituencies. However, improvements in yields made possible by nearby forest protection may be relatively small in places where significant increases in productivity are possible through alternative interventions—such as introducing improved climate-appropriate seed sources or fertilizer use where there is none—as may be the case for applying best available practices to smallholder oil palm cultivation in Southeast Asia.

Jurisdictional Approaches to Deforestation-Free Commodity Supply Chains

So-called *jurisdictional approaches* (Wolosin 2016) could be a promising policy context for introducing greater consideration of local forest-climate interactions in several soy-producing Brazilian states. At COP21 in 2015, the governor of Mato Grosso introduced his state's "Produce, Include, Conserve" strategy for growing agricultural production while protecting forests, which emerged from a multistakeholder process including government, civil society, companies, and investors (EII Newsroom 2015). The strategy pulls together several policy approaches—including REDD+, improved land sector governance, and meeting zero-deforestation supply chain demand—into a coherent and shared set of targets and actions. Related jurisdictional approaches are advancing in many of Brazil's soy-producing states (GCF Task Force 2021).

These state-level policy venues could present several advantages. Most importantly, the agriculture industry—including individual companies, large landowners, and industry associations—is already at the table and playing a constructive role in the development of land-use policies and strategies. It is thus well primed to take into consideration the interactions between deforestation and agriculture. These state governments already have support for better managing and governing land-use change in these states; their ongoing implementation of these goals—including through mapping land tenure and monitoring as well as enforcement—would provide fertile opportunities for incorporating local biophysical climate impacts into policy models. There are also potential opportunities for farmers participating in these jurisdictional-scale approaches to capture the economic value of forests' local climate (and thus crop productivity) stabilization through financial incentives linked to reduced risk of crop failures—such as reduced insurance costs or reduced rates for agricultural loans. A next step to support such public or private sector initiatives would be to attempt a mapping of the local climate benefits of forests to the specific areas affected, testing the limits of recent advances in spatial analysis. Such "action maps" have been produced for silvopasture expansion (Vargas Zeppetello et al. 2022), for example.

Climate Adaptation Mainstreamed into Agricultural Planning

A long-standing approach to national and subnational-scale climate policy implementation has been to incorporate climate considerations into sectoral policy—often referred to as climate policy integration or *climate mainstreaming* (di Gregorio et al. 2016). Venues and instruments that already have wide adoption in the agriculture sector are likely routes to introducing consideration of heat stress risks from forest cover change into a traditionally conservative Ministry of Agriculture that has prioritized economic growth and expansion over environmental objectives (Milhorance et al. 2021). These observations lead us to ask, Where have concerns about crop productivity in a warming climate already been mainstreamed into instruments widely adopted by the Ministry of Agriculture?

Land-use systems and the forest/agriculture nexus are at the heart of Brazil's climate policy planning, because of the vulnerability of ecosystems and agricultural productivity to climate change and because of the mitigation opportunities presented by both. The National Forum on Climate Change and the Inter-ministerial Committee on Climate Change are the primary policymaking venues for Brazil's National Policy on Climate Change and subsidiary instruments such as the National REDD+ Strategy, the Plan for Consolidation of a Low Carbon Economy in Agriculture, and the National Adaptation Plan (NAP).

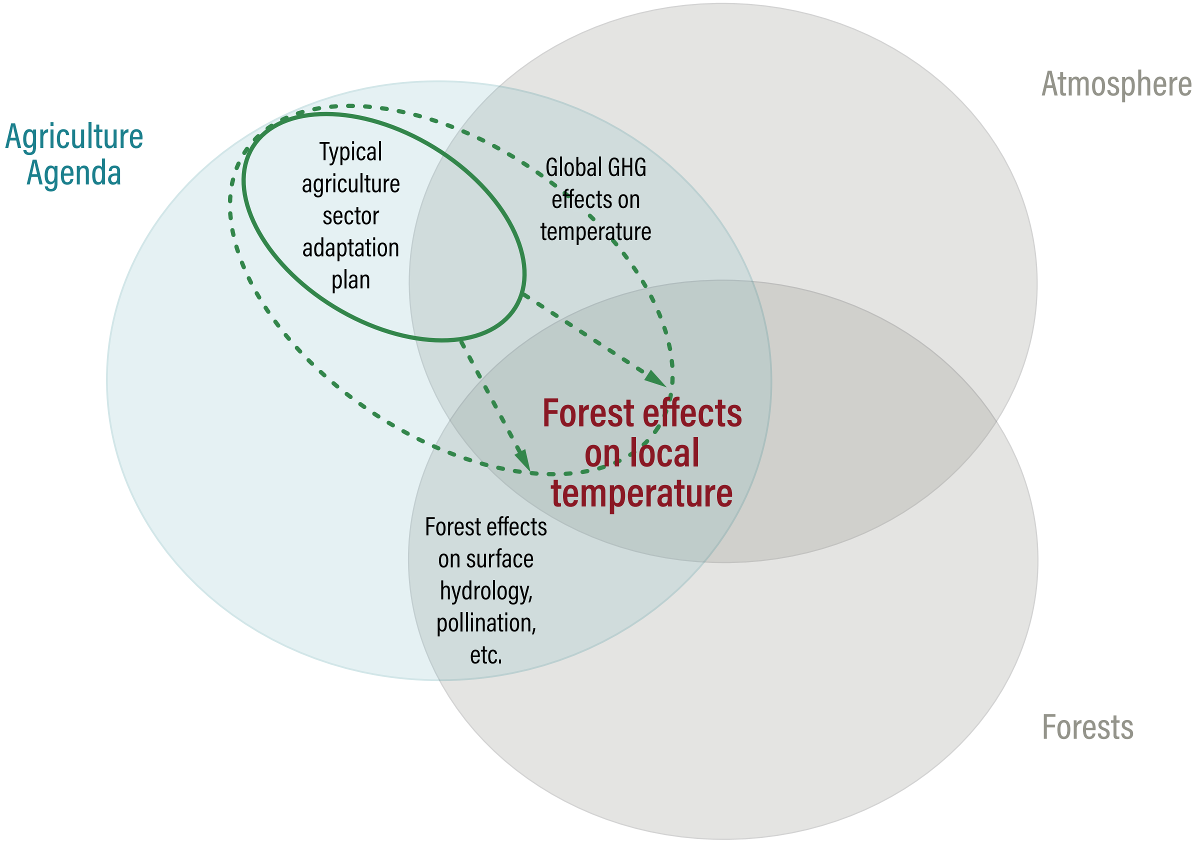
While adaptation action has been neither as well funded nor as well developed as REDD+ (di Gregorio et al. 2016), it *has* been mainstreamed into agriculture policy with a focus on planning and risk avoidance—exactly the right policy modes for relevant consideration of local forest-climate heat stress. The NAP makes explicit that adaptation is a necessary goal of long-standing land-use planning instruments like "agroecological zoning." This technical-scientific instrument for agricultural spatial planning delimits areas that are deemed "appropriate" for development of various crops based on climate, soil, vegetation, and other biophysical, social, and economic characteristics. One of its goals is to guide decision-makers in establishing public policies related to agricultural development programs, and the maps it produces are used, for example, to determine access to public finance (Embrapa n.d.).

The Agroecological Zoning and related Agricultural Climate Risk Zoning processes could begin to consider deforestation-driven heat impacts on soy production in several ways. For example, modeling could be extended to include temperature feedbacks from nearby forest clearing in individual locations, or to examine crop- and industry-scale development scenarios that explicitly model productivity losses from local temperature impacts that result from different scales and/or patterns of expansion. These types of additional information would speak directly to actors who are undertaking forest clearing for agriculture, drawing attention to the heat stress feedbacks and risks such clearing entails.

These processes have several attractive features as policy contexts. They are run by Embrapa, the research arm of the Ministry of Agriculture, but are implemented through the work of multidisciplinary and multi-institutional teams and external public tenders. Their products are already incorporated into implementation instruments like public finance. And they are broadly adopted across Brazil, with zoning maps developed at the state level for all economically significant crops.

Figure 5.2 illustrates how recognition of the non-carbon climate impacts of forests on agriculture expands the areas of overlap between agriculture, forest, and climate policies with the example of planning for adaptation.

FIGURE 5.2 | Deforestation, Heat Stress, and Agricultural Productivity Policy Contexts: Venn Diagram



Source: Authors.

HUMAN HEALTH, TEMPERATURE, AND DEFORESTATION

Linking Deforestation to Human Health Impacts

Heat exposure presents significant health risks to communities around the globe and is a major area of climate policy concern—and not just in developing countries: hundreds died during extreme heat waves in western North America in 2021 and in Europe in 2022. Wherever people must work outside in the heat, or inside in non-air-conditioned spaces, or lack access to sufficient water, shelter, or cooling, a warming climate can impact cognitive performance, work output, income, and overall human health. Exposure to heat in the workplace can also exacerbate chronic health problems, including cardiovascular and kidney disease. Further, the types of employment common on deforestation frontiers tend to be informal, and not effectively addressed by worker safety regulations and enforcement.

With the link between deforestation and local warming clearly established, one might ask, How is this deforestation-driven increase in average and extreme temperatures affecting local communities directly through their health and well-being? And how do those impacts relate to those of temperature increases caused by global warming?

These are exactly the questions a multidisciplinary team of social, health, climate, and forest scientists from The Nature Conservancy; University of California, San Diego; University of Washington; and Mulawarman University have been asking about *in situ* impacts of deforestation in Berau District of East Kalimantan (on the island of Borneo) in Indonesia. Berau is the site of a jurisdictional REDD+ program that was developed by The Nature Conservancy in partnership with the district government and launched in 2010, pursuing a range of strategies across governance, capacity-building, and alternative livelihoods (Hovani et al. 2018).

The results of this team's research on human health impacts in Borneo have been striking. Social surveys from nearly 500 villages across the island showed that local communities have a clear understanding of the importance of forests in maintaining cool local temperatures—particularly so in villages that already have particularly hot or variable temperatures, and in villages with more recent deforestation (Wolff et al. 2018). Observational data show that workers in open, exposed areas experience ambient temperatures 2.6°–8.3°C warmer than in forests and up to 6.5 hours of exposure to temperatures above well-being thresholds (Masuda et al. 2019).

A randomized controlled trial of workers assigned to typical outdoor work in deforested vs. forested areas showed increased heart rates, core body temperatures, and heat stress in the deforested areas (Suter et al. 2019). A subsequent and similar experiment documented measurable cognitive declines resulting from deforestation-caused heat exposure, especially for males and for afternoon work (Masuda et al. 2020). The team documented worker productivity declines of over 8 percent in deforested areas where wet bulb globe temperatures—a measure of heat exposure that combines temperature, humidity, and sun exposure—were, on average, 2.84°C higher, driven by workers taking more breaks to adapt to the heat, with impacts on both work speed and quality (Masuda et al. 2021).

More recently, the team used spatially explicit data on forest cover, temperature, population, and climate models to estimate the impacts of increased temperatures on mortality and unsafe working conditions in the district (Wolff et al. 2021). They found that deforestation of 17 percent of the district's area over the period 2002–18 had increased the mean daily maximum temperatures by 0.95°C. This forest cover loss led to an additional 20 minutes of unsafe working conditions each day in deforested areas (10 times the increase modeled in forested areas) and an estimated 101–118 additional deaths in 2018, accounting for 7.3–8.5 percent of all-cause mortality in 2018. They projected that even without further forest cover change, deforested areas could experience an increase of 17–20 percent in mortality from all causes, and up to five hours of unsafe working conditions each day if the planet were to warm an additional 2°C. These effects are comparable in magnitude to several of the notable public health challenges in the region, such as smoking, respiratory infections, and transportation-related injuries.

BOX 5.2 | Temperature, Trees, and Human Health—Not Just Indonesia

Strong impacts on human health from deforestation-related local warming are also expected in the Amazon region and across the tropics.[a] Alves de Oliveira et al. (2021)[b] simulate late-century climatic conditions in Brazil under different emissions and deforestation scenarios and find that expected human heat stress in 2100 due to widespread deforestation and no further emissions-based warming would be comparable to that expected from 8.5°C warming from emissions alone with no further deforestation. The study indicates that large-scale deforestation of the Amazon Rainforest would expose residents of northern Brazil to temperatures that exceed the physiological limits of the human body.

Recent related modeling research indicates that humid heat impacts may be severely underestimated, given advances in understanding of biophysical limits to humid heat exposure—impacts of heat on outdoor workers engaged in heavy labor being nearly 2.7 times higher than previous estimates.[c]

The local temperature-moderating benefits of trees on human health have also been the focus of significant policy attention with respect to climate adaptation in urban areas. In just the last year, new research has revealed extreme "tree inequity" in U.S. urban areas, with far fewer trees in low-income neighborhoods and in communities of color, and with much hotter temperatures and heat exposure as a result.[d] President Joe Biden recently proposed a Civilian Climate Corps with significant funding to plant trees in urban areas where they are currently lacking, as an adaptation and racial justice measure.[e]

Sources: a. Parsons et al. 2021, b. Alves de Oliveira et al. 2021, c. Parsons et al. 2022, d. Brown 2021, e. Daly 2021.

These district-level findings have broader significance for Indonesia and for tropical and non-tropical countries globally (Box 5.2). Indonesia, which along with its neighbor Malaysia produces the vast majority of the world's palm oil (USDA "Palm Oil Explorer" 2021b). According to Global Forest Watch, oil palm plantations replaced 10.5 million hectares of forests globally during the period 2001–15, and more than two-thirds of this conversion—some 7 million hectares—occurred in Indonesia, with especially large areas in provinces of East and Central Kalimantan and Riau in Sumatra (WRI 2020). In recent years, deforestation in Indonesia, including forest clearing attributable to expansion of oil palm plantations, has been on a downward trajectory, one of the few bright spots in an otherwise bleak landscape of global trends in forest loss (Weisse and Goldman 2021). However, the findings of the research summarized above imply that previous clearing has left a legacy of human health vulnerability to elevated temperatures that the country will be dealing with for years to come, even if deforestation were to be halted.

Deforestation, Temperature, and Human Health Impacts: Relevant Policy Contexts

The clear evidence that deforestation results in higher average and extreme temperatures, and that exposure to such temperatures affects the physical and mental capacity of outdoor workers, could be addressed in several different policy contexts in Indonesia and elsewhere. Some policy approaches focus on incorporating heat stress risks into decisions to deforest, while others focus on adapting to the elevated risk of heat stress that results from land-use change. We briefly sketch several such approaches here, with examples from Indonesia and more broadly, to illustrate associated challenges and opportunities.

Heat Stress Risk Considered in Worker Safety Regulations

As global climate change brings increased average and record-breaking extreme temperatures, increased morbidity and mortality resulting from heat stress is now recognized as a significant risk requiring an integrated policy response. The U.S. federal government launched such a response in 2021, following an unprecedented heat wave in the Pacific Northwest that caused 3,500 people to head to emergency rooms in four states (Ryan 2021), and an estimated 600 excess deaths in Washington and Oregon alone (Popovich and Choi-Schagrin 2021). Among the initiatives announced was an effort by the U.S. Department of Labor to protect outdoor workers, including those in the agriculture and construction sectors, from exposure to extreme heat (White House 2021). The administration highlighted the environmental justice dimensions of the initiative, noting that Black and Brown workers were disproportionately represented among those exposed to occupational heat hazards.

Outdoor workers in tropical countries such as Indonesia and Brazil, and those laboring indoors in non-air-conditioned spaces, face severe and increasing risks of heat stress as the planet warms (Romanello et al. 2021). Working in extreme heat risks dehydration, decreases worker productivity, and increases the risk of workplace accidents due to cognitive impairment.

For agricultural workers, heat stress can compound existing occupational risks from pesticide use. Guidelines jointly published by the UN Food and Agriculture Organization and the World Health Organization note that limiting pesticide exposure faces special challenges in low- and middle-income countries, especially in hot and humid tropical climates (FAO and WHO 2020). The guidance notes that workers may be less likely to wear personal protective equipment due to heat-related discomfort (increasing pesticide exposure) or be more vulnerable to heat stress resulting from having to wear such equipment. Further, sweating can increase the absorption of chemicals through the skin, and heat-related cognitive impairment can increase the risk of accidental exposure.

These examples highlight policy contexts and venues that are identifying and trying to address both direct and indirect human health risks—and it is clear that these risks are further increased by the local impacts of deforestation on temperature. Worker safety initiatives need to factor in elevated risks of heat stress attributable to both global warming and higher temperatures due to nearby forest loss and interactions between heat stress and pesticide exposure risk. Regulatory bodies could, for example, provide guidance regarding how employers should mitigate those risks through interventions such as adjustment of working hours, frequency of breaks, and access to water and cooling spaces. Several frameworks on worker safety can be used to guide such processes (Spector et al. 2019). The spatial variability of temperature increases also suggests that human health risk mitigation guidance cannot simply rely on average temperatures, or even expected daily extremes—the extremes observed in deforested areas suggest that site-based monitoring may also be needed. Clearly, workers such as those laboring in oil palm plantations described in the opening of this chapter are especially vulnerable.

Considering Deforestation as a Public Health Issue

Increased exposure to heat stress is only one of several linkages between deforestation and human health. Healthy forests contribute to the maintenance of healthy human communities by providing both goods and services, while deforestation and degradation can adversely affect access to those goods and services. Forest fruits, nuts, and bushmeat contribute to more diverse and nutrient-rich diets. Pharmaceutically active compounds extracted from both plants and animals are the basis for many traditional and modern medicines (Seymour and Busch 2016). Forests also contribute to air and water quality. In Indonesia, smoke from the catastrophic fires of 2015—fueled by forest and peatland degradation—were estimated to have caused some 100,000 excess deaths in the Southeast Asia region (Koplitz et al. 2016). Riparian forests filter sediments and pollution out of surface water: conversion of forests to oil palm plantations in Indonesia increases the sediment load of streams by up to 550 times (Carlson et al. 2014). Land clearing for agriculture has been linked to a higher incidence of various vector-borne diseases, and the COVID-19 pandemic has increased scrutiny of how forest disturbance can increase the risk of transmission of zoonotic viruses. The Harvard-based Scientific Task Force for Preventing Pandemics at the Source (PPATS) identified forest conservation as a key response to reducing that risk (Alimi et al. 2021).

Unhealthy forests don't just lead to unhealthy people—causality can run in the other direction as well. Ironically, the high cost of access to health services can itself be a cause of forest loss, as low-income households resort to illegal logging as a way to generate funds to pay clinic fees. The Health and Harmony initiative in West Kalimantan, Indonesia, demonstrated that conditional access to discounted health services in association with complementary environmental education and livelihoods support reduced illegal logging adjacent to the villages most engaged in the program, while also improving health outcomes (Jones et al. 2020).

For all of these reasons, deforestation should clearly be considered a public health issue, but it is rarely mainstreamed into public health planning and decision-making, much less public health budgets, which dwarf expenditures for forest protection and restoration. In Indonesia, for example, prepandemic annual government expenditures for health averaged around \$32.4 billion,[13] while the budget available under the current National Medium-Term Development Plan (RJPMN 2020–24) for achieving the government's target of turning the nation's forests and peatlands into a net sink by 2030 averages only \$271.2 million per year, when almost five times that much is estimated to be needed (GOI 2022).

Framing the loss of local forest services as a threat to local human health is also more likely to gain political traction than appeals to protecting their global values for climate change mitigation or biological diversity conservation. The health impacts of forest loss are more immediately and locally felt and are more subject to the influence of local actors. Historically across countries, public awareness of environmental action and support for government regulation have often been most pronounced when environmental degradation was understood as a threat to human health. Legislation in the 1970s to address air and water quality and release of toxic chemicals in the United States followed this pattern (U.S. EPA 2021). In Indonesia, it is notable that despite numerous presidential-level pledges to tackle deforestation earlier in the decade, it was only after the 2015 fires—and their devastating impacts on public health—that political will sufficient to bend the trajectory of forest loss was brought to bear on the issue.

Recent efforts to integrate improvement of public health and protection of the natural environment are promising (Whitmee et al. 2015). Box 5.3 describes a global-level initiative to link the COVID-19 pandemic to forest loss as well as how its approach might be expanded to address the linkages between deforestation and increased exposure to heat stress.

BOX 5.3 | Breaking Down Silos between Forests and Health

A policy analogue at the global level is provided by Preventing Pandemics at the Source (PPATS), an initiative formed in response to the COVID-19 pandemic. The initiative brings together grassroots health activists, international health professionals, and mainstream conservation and wildlife organizations. Collectively, PPATS attempts to break down the silos between the two issue areas by supporting scientific research and advocating for policies that recognize their interconnections. Similar coalitions could be replicated at national and subnational levels to highlight the public health issues at stake in land-use decision-making, and perhaps be broadened to include labor organizations. Such coalitions could raise awareness of the increased risk of heat stress exposure to rural workers as part of a broader agenda, and advocate for greater integration of public health and forest management in regulatory actions and budgetary allocations.

Source: PPATS n.d.

Climate Adaptation Mainstreamed into Land-Use Planning

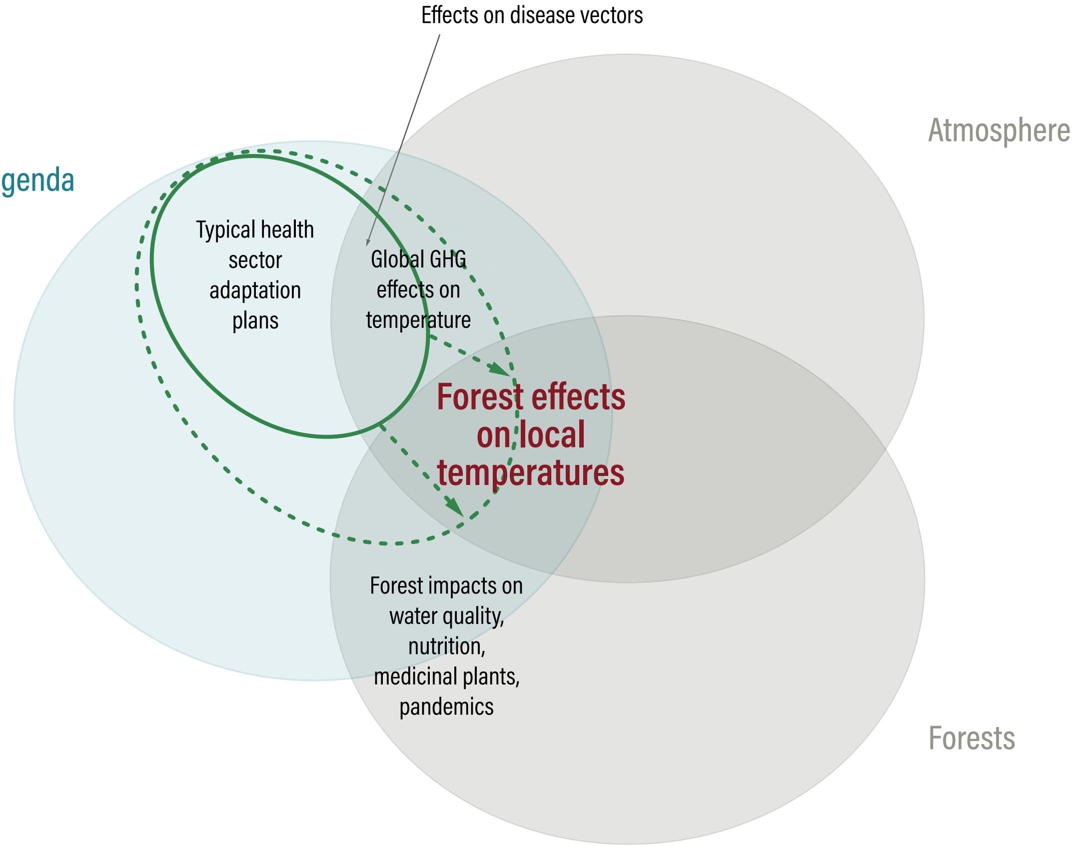
The section earlier in this chapter focuses on the temperature effects of land-use change on crop productivity and describes how this issue could be factored into agriculture sector adaptation planning in Brazil. Similar opportunities are available in Indonesia to incorporate deforestation-related temperature effects on public health and worker safety into adaptation strategies and land-use planning. Opportunities to link these objectives to national REDD+ programs and jurisdictional-scale efforts to get deforestation out of commodity supply chains are also available in Indonesia but will not be explored further here.

Indonesia's Long-Term Strategy for Low Carbon and Climate Resilience includes as its first pillar a focus on human resources, including improved health and quality of life, and enhanced productivity (GOI 2021, 13–14). Further, the strategy recognizes a need for vertical and horizontal integration across Agriculture, Forestry, and Health Ministries (among others) for adaptation (GOI 2021, 115). However, a review of the strategy suggests that anticipated economic and health impacts of increased temperatures are based on downscaled global IPCC scenarios, and do not yet take into account the local compounding effects of forest cover change—which Figure 5.1 above shows may be several times higher than the global warming increases alone (GOI 2021, 103). Meanwhile, the impact on the health sector was analyzed based on the changed area affected by vector-borne disease simulated using the projections of climate models. Moreover, while the strategy considers urban heat islands as a health risk as well as the implications for building codes, it does not address the impacts of heat stress in rural areas and necessary labor policy interventions.

An instrument for addressing these omissions could be the Strategic Environmental Assessments established in 2016 under Government Regulation No. 46 (GOI 2021, 110). The regulation provides a strong legal basis for integrated, comprehensive, spatially explicit land-use planning at the national and subnational levels, by adopting a landscape-based approach to ecosystem management to ensure food, water, and energy security. An initiative in three districts of North Sumatra led by Conservation International and supported by U.S. bilateral funds pioneered the Strategic Environmental Assessment process in 2013–16 as a way to mainstream forest protection values into the districts' Medium-Term Development Plans (CI 2016).

Figure 5.3 illustrates how recognition of the non-carbon climate impacts of forests on human health expands the areas of overlap between public health, forest, and climate policies, with the example of adaptation planning. Such recognition will require figuring out how to assess and prioritize the indirect benefits of forest protection for health, to enable comparisons to more direct or targeted adaptation measures.

FIGURE 5.3 | Deforestation, Temperature, and Human Health Policy Contexts: Venn Diagram



Note: GHG = Greenhouse gas..

Source: Authors.

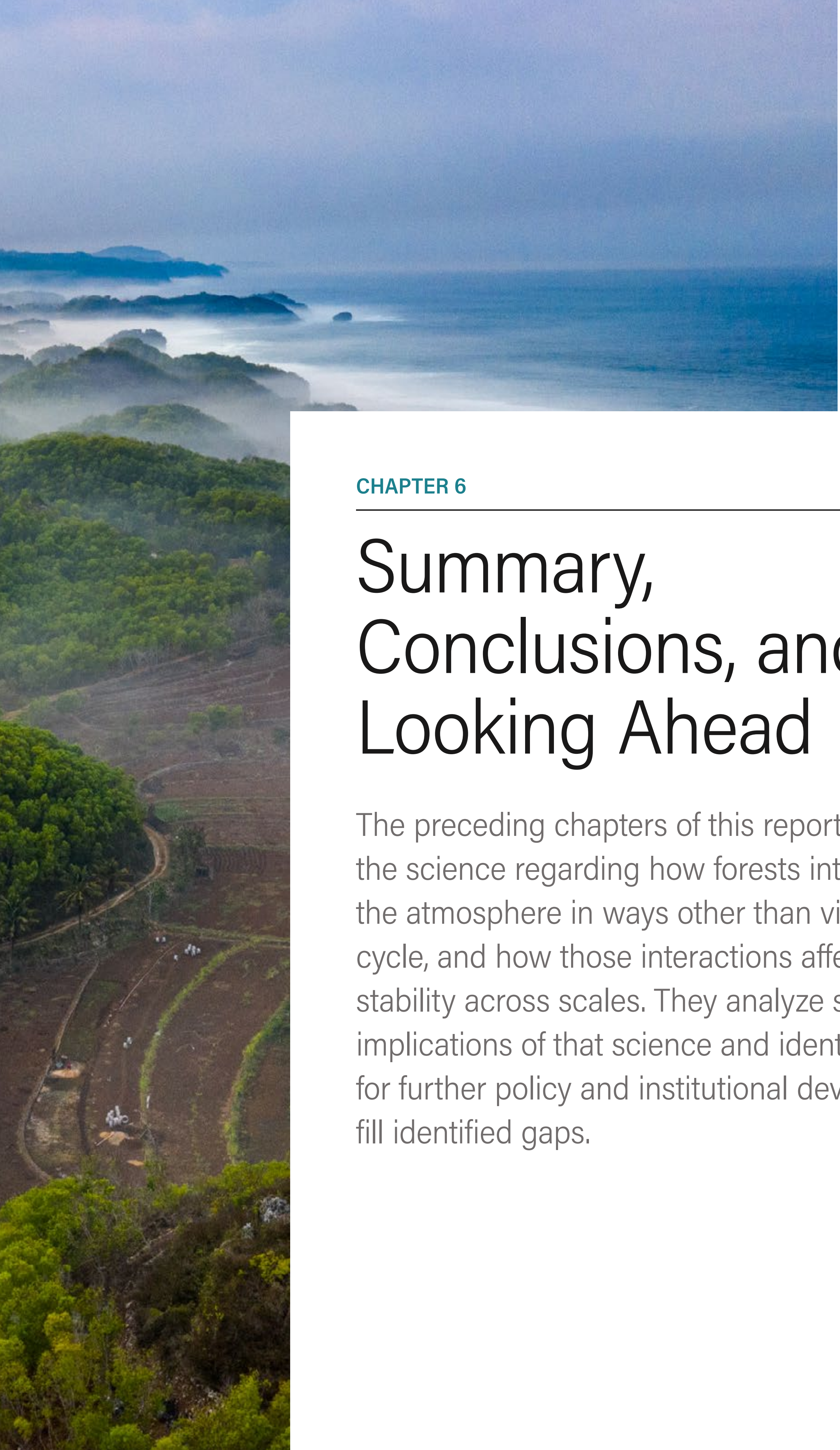
CONCLUSIONS

The analysis presented above has raised a number of policy implications that we summarize here.

First, the science is clear that the local effects of deforestation on temperature, and in turn the impacts of extreme temperatures on crop productivity and human health, are already being felt, especially in the tropics. These effects on local temperatures are more immediate than, and are exacerbated by, those due to global warming. Thus, the climate effects of local deforestation should be urgently addressed in national and local adaptation planning, but they are currently ignored. While the "urban heat island" effect is well recognized and often addressed in adaptation planning, rural heating caused by deforestation is not.

Second, the adverse economic implications of forest loss for rural areas through non-carbon climate effects are multiple, and in some cases compounding, affecting the productivity of agricultural crops as well as human health, and the productivity of human labor. These impacts in turn have multiple implications for environmental justice, with developing countries in the tropics facing the most extreme temperatures, and small farmers and agricultural workers least able to adapt to these productivity losses.

Third, addressing these policy implications will require breaking down silos across sectoral agencies and stakeholder groups. Optimizing land-use planning for a changing climate requires the joint consideration of objectives related to agricultural production, protection of public health and worker safety, and climate adaptation planning, and the implications of deforestation for all of those objectives. Continued forest loss at current rates will guarantee a suboptimal outcome for farmers and rural workers, as well as for the broader societies that depend on the food that they produce.



CHAPTER 6

Summary, Conclusions, and Looking Ahead

The preceding chapters of this report summarize the science regarding how forests interact with the atmosphere in ways other than via the carbon cycle, and how those interactions affect climate stability across scales. They analyze selected policy implications of that science and identify directions for further policy and institutional development to fill identified gaps.

Our overarching message is that forests have significant, well-established—and overwhelmingly positive—effects on climate stability that are not sufficiently recognized in current policy frameworks. These policy gaps result in systematic undervaluing of forests for the climate services they provide to people, failures to anticipate the full range of impacts of forest loss, and a lack of knowledge and consideration of forests' services to human health and agriculture.

Although storing carbon is the most significant way forests cool the climate globally, the biophysical effects of forest cover can either amplify or dampen that global cooling effect. The relative magnitude of those biophysical effects compared to that of carbon storage depends both on the latitude of the forests and background climate of the area where they are located, with humid tropical forests providing the greatest amplification of forests' global cooling services. Further, the local and regional impacts of forest loss on temperature and rainfall via biophysical processes are more immediately felt and can be more significant in the near term than the local effects of global warming resulting from all sources of GHG emissions.

These impacts have implications not just for climate policy but also for multiple sectoral policy agendas, as well as for equity within and between countries. For example, the health and well-being of Indigenous and other forest-reliant communities, who have contributed the least to global climate change, are especially vulnerable to the loss of ecosystem services. As the stewards of large expanses of tropical forests, they would stand to benefit if the biophysical global cooling effects of forests were recognized and rewarded with commensurate flows of climate finance.

Before advancing general conclusions from a synthesis of our policy analyses, we recall the top-level messages from each of the preceding chapters here.

SUMMARY

The Science

Forests affect the climate across scales through multiple pathways in addition to the carbon cycle. At the global level, the effect of forest cover on albedo varies by latitude, with cooling effects in the tropics and warming effects in boreal areas. Evapotranspiration transforms surface and soil water into water vapor in the air and provides a local cooling effect. Both the water vapor and the cooler air temperatures are transported by, and affect, atmospheric circulation patterns at larger scales. The surface roughness of forest canopies creates wind turbulence, and thus affects the distribution of heat and moisture vertically in the atmosphere. The small particles released by forests—including volatile chemical compounds, pollen, and ash—interact with each other and water vapor to affect cloud formation, and thus albedo. While the impacts of GHG fluxes and albedo on the global climate are relatively well understood, the specific impacts of deforestation and land-use change across scales on local and regional weather and rainfall via evapotranspiration and cloud formation are more complex, location-specific, and difficult to predict.

Taken together, these multiple and interlinked interactions between forests and the atmosphere mean that forests are part of global, regional, and local climate *systems*—they are not merely forcers of global temperature change through their storage and release of carbon. In that sense, forests are categorically dissimilar to other sources of GHG emissions and removals. Deforestation unravels multiple threads of the fabric of climate stability in ways that are fundamentally different than extracting and burning fossil fuels.

Global Policy Implications

The primary venue for governance of global climate change, the UNFCCC, has defined its scope and mandate around limiting the accumulation of GHGs in the atmosphere. Although the framing of the Paris Agreement around temperature goals provides a subtle but important shift, consideration of biophysical global climate forcings have remained largely on the sidelines of global climate policy and accounting.

Neglecting biophysical global warming and cooling is especially salient for forests. In particular, tropical forests provide global climate benefits through biophysical effects above and beyond carbon emissions, storage, and capture that are large enough to be globally significant for achieving climate goals. By not accounting for these additional global climate benefits of tropical forests, international climate policy is undervaluing tropical forests and the actions that tropical countries can take to slow and reverse forest loss—

and may conversely be overvaluing northern forests in global accounting. Moving toward incorporating those impacts into the global climate policy regime would improve our understanding of how we can most effectively, efficiently, and equitably achieve climate goals.

There are several ways that international climate policy could continue to prioritize the protection and restoration of tropical forests. These may include the following:

- Adjusting national GHG accounting to reflect latitudinal differences in the global impacts of forest cover change (in terms of CO_2-equivalent impacts on global temperature via biophysical pathways, including albedo)
- Redoubling support for REDD+, and recognition of biophysical effects as both globally and locally valuable cobenefits of forest protection and restoration, including in the context of voluntary carbon markets
- Enhancing recognition of the contributions of forests to adaptation objectives, and consideration of adaptation finance for forest protection and restoration alongside other adaptation priorities

Regional Policy Implications

Forests can affect rainfall patterns at continental scales through their role in affecting cloud formation and wind patterns and evapotranspiration. Large expanses of forest serve as precipitationsheds for downwind areas spanning national boundaries. By destabilizing rainfall at great distances, deforestation in upwind countries can have profound impacts on agricultural productivity, hydropower generation, and drinking water supplies in downwind countries.

Although many regional-scale international agreements and institutions have been constructed to address the management of transboundary surface water flows, there is as yet limited experience with governance mechanisms to address moisture transported through the atmosphere. Although such moisture transport affects the blue water flows governed by transboundary water management institutions, it is ignored by these existing institutions—perhaps appropriately, as the composition of countries implicated in the management of watersheds and precipitationsheds is often different.

Nevertheless, watershed management institutions offer relevant models and lessons, as do institutions constructed to manage transboundary air pollution. Policy directions for addressing the precipitationshed governance gap may include the following:

- Raising awareness and establishing norms related to transboundary atmospheric moisture issues and management
- Adapting the coverage and mandates of existing transboundary river basin authorities, and creating new institutions where necessary
- Exploring the potential of financial instruments such as transboundary payment for environmental services schemes

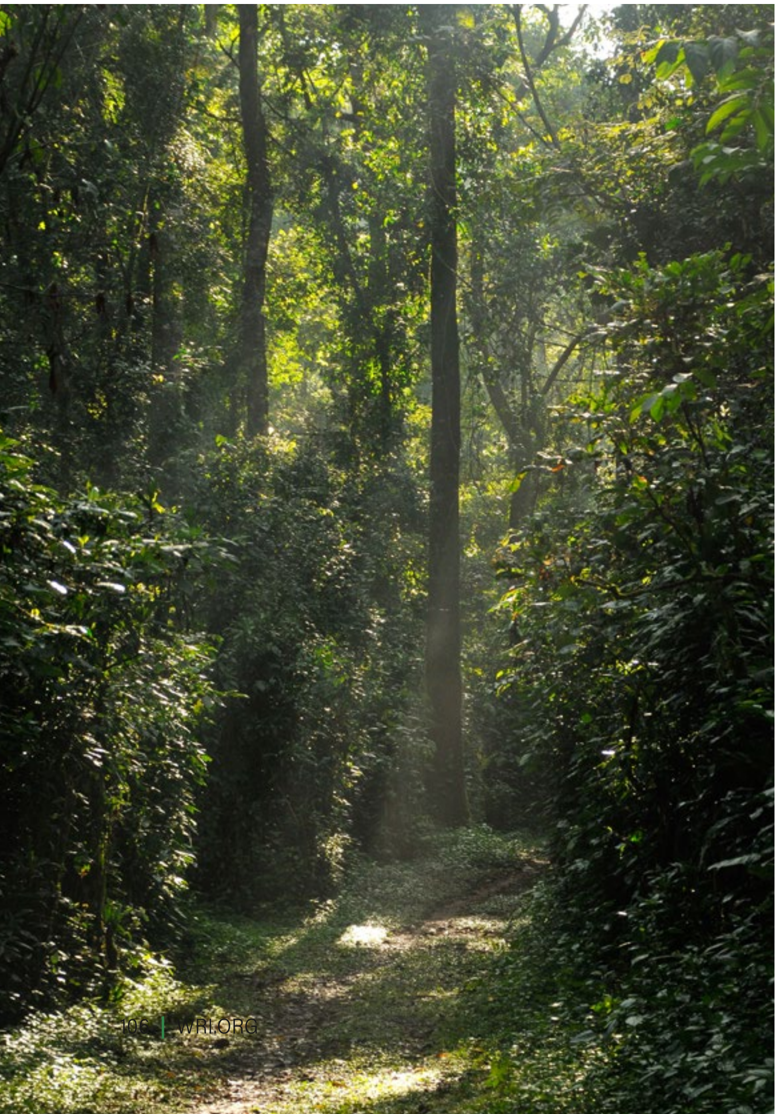
National and Local Policy Implications

All forests provide local climate benefits through biophysical effects, and the loss of those benefits can have more significant impacts on human well-being in the near term than the local effects of global climate change. In particular, forest cover affects not just average temperatures on the earth's surface, but also temperature extremes. The risks to agricultural productivity posed by deforestation, especially when combined with the rainfall disturbances described above, are clear, and already being observed. The implications of temperature extremes for human health, and particularly the increased risks of heat stress to outdoor workers, are similarly large.

In part because they have rarely been quantified, the benefits of maintaining forests are currently underappreciated in the context of planning for climate risk mitigation and adaptation at national and local scales. Recognition and quantification of such benefits could be elevated in national and local policy arenas as well as in international climate adaptation policy and discourse to provide the necessary finance for implementation.

Policy responses include those designed to prevent the adverse local effects of forest cover loss by factoring their costs into land-use decision-making, as well as those designed to adapt to those effects after deforestation has taken place. Illustrative policy directions include the following:

- Integrating the direct effects of forest loss on agricultural productivity into the agriculture sector and local land-use planning
- Drawing agricultural producers into REDD+ processes in ways that emphasize their roles as *beneficiaries* of the local climate stability afforded by forest cover
- Considering forest protection as a public health intervention to reduce the risk of rural heat stress (as well as the risk of pandemics)
- Taking deforestation-induced rural heat stress into account in worker safety regulations
- Integrating the temperature effects of deforestation on agriculture and human health into climate adaptation planning



The policy directions noted above span a range of options, some of which are more feasible than others in the near term due to technical or political constraints. For example, incorporating forests' biophysical effects into financial decision-making will in some cases depend on advances in measuring their spatial extent and valuation of their economic impacts. Responses by national and local decision-makers acting on their own self-interest (or that of the constituencies they represent) within the scope of their current authority are more likely in the near term than those that depend on negotiations among sovereign governments. Nevertheless, the importance and urgency of initiating action is clear.

CONCLUSIONS

We now distill our policy analyses into five broad implications.

> **Policy approaches to address the role of forests in global climate mitigation need to broaden in scope beyond greenhouse gas emissions (GHGs) to include the biophysical effects of forest cover on keeping the planet cool.**

International policy related to climate mitigation has been typically limited to GHG emission reductions and removals. As elaborated in Chapter 2, such a limitation fails to take into account the many biophysical pathways through which forests affect climate stability, including at the global scale. As described in Chapter 3, the framing of the goals of the Paris Agreement in terms of maximum *temperature* targets, rather than in terms of limitations on GHG concentrations in the atmosphere, provides a critical opening for expanding the scope of the UNFCCC beyond its original narrower focus—in other words, the Convention text enables policymakers to act now. Indeed, a better understanding of the non-carbon impacts of forests on the global climate is critical to include in the ongoing Global Stocktake under the UNFCCC, which is assessing collective progress toward the long-term goals of the Paris Agreement.

As already highlighted above, the most critical aspect of this expansion is to incorporate the significant biophysical net cooling effects of tropical forests on the global climate, and thus their current undervaluation based on GHG-only accounting in inventories, NDCs, and REDD+. In addition, however, consideration of biophysical processes has implications for the inclusion of forests in other latitudes in climate policy and associated accounting systems. Specifically, in the midlatitudes, forests provide net global benefits from GHGs and biophysical effects together, but less than their GHG-only effects. Reducing and reversing midlatitude forest loss provides net global cooling and will continue to be an important strategy for mitigating carbon emissions but *may* be overvalued in international climate policies where they can be treated as fully fungible with fossil emissions. In the boreal zone, forests' biophysical warming effects exceed their GHG cooling effects due to the counterbalancing weight of albedo. Thus, expanding boreal forest cover has local benefits and multiple nonclimate benefits for people and nature but is not a *global* cooling strategy.

Achieving policy coherence requires consideration of both GHG and non-GHG global temperature effects. Such coherence in turn depends on the alignment of the scientific community and countries on their approaches to the analysis, understanding, and quantification of biophysical forest effects on global average temperatures and local climate benefits, particularly in the context of forestry and land-use change across the tropical-temperate-boreal gradient. Otherwise, we run the risk of over- or under investment in forests as a global warming solution, or "leakage" of global surface temperature change drivers from one place to another or from one process (e.g., GHGs) to another (e.g., albedo). However, in both the midlatitudes and the boreal zone, forests provide significant local and regional climate regulation benefits, suggesting that they are an important climate stabilization strategy for people on the ground everywhere.

> **Policy approaches to achieving climate stability goals need to be inserted into new policy arenas to address the biophysical impacts of forest loss across scales.**

Climate change has typically been understood to be a *global* problem with *global* solutions to be addressed through *global* governance mechanisms such as the UNFCCC. While it has long been recognized that adaptation to climate change has inherently local dimensions, the focus of mitigation efforts on managing emissions of GHGs has obscured the additional ways that forest cover change is affecting regional as well as national and local climate stability.

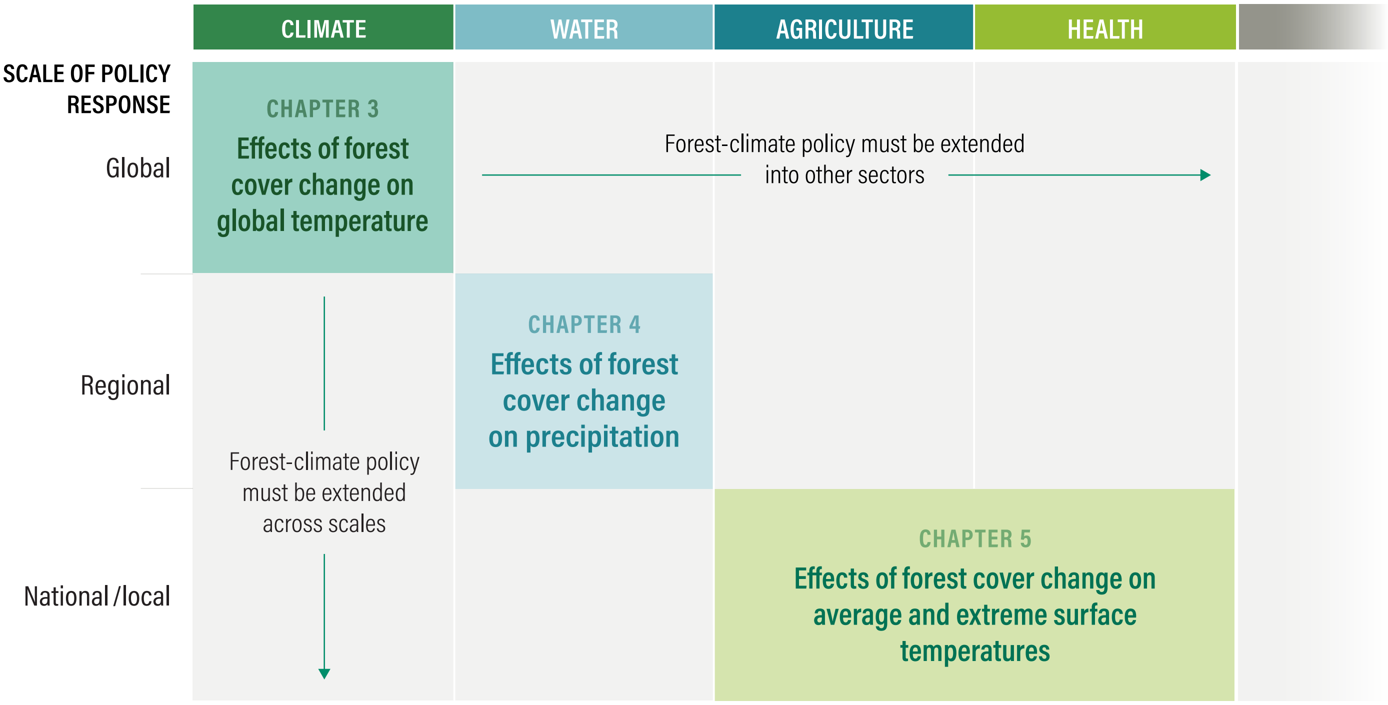
Although global warming due to the greenhouse effect is expected to affect rainfall patterns around the world, forest cover change can also affect precipitation at regional scales as described in Chapter 4. Yet neither global climate forums nor national land-use policies provide a governance mechanism for mediating among the interests of stakeholders in upwind countries in precipitationsheds and those in downwind countries affected by their decisions. The effects of deforestation on regional rainfall patterns need to be addressed in transboundary agreements and institutions.

In addition, the local cooling and rainfall effects of forest cover change need to be considered in conjunction with the effects on local climate stability mediated through global warming. National and local climate adaptation plans based on downscaled models of the local impacts of global temperature rise will fail to capture the compounding effects of local climate disruption due to deforestation—or the potential compounding benefits of local climate moderation from potential tree cover expansion.

In some cases, this extension of climate policy across scales and policy areas can be expected to increase political support for climate action through forest protection. For example, understanding the loss of forest services as a threat to local human health is more likely to gain political traction than appeals to their global values for climate change mitigation or biological diversity conservation, because the problem is both more directly and immediately felt, and is more amenable to local control.

> Extension of climate policy across scales and policy areas can be expected to increase political support for climate action through forest protection.

FIGURE 6.1 | Accounting for the Full Impacts of Forests on Climate Requires Policy Attention to Extend from Global to Local Scales and across Sectors



Note: GHG = Greenhouse gas. Shaded cells are examples highlighted in this report.
Source: Authors.

As illustrated in Figure 6.1, closing current policy gaps across this "vertical" dimension of governance and spatial scales requires expanding consideration of the issues from the global level into regional, national, and local policy arenas to capture the full range of forests' impacts on climate stability.

> **Capturing the benefits of forests for climate mitigation, adaptation, and other objectives requires breaking down the barriers between siloed policy arenas.**

In addition to the need to expand policy approaches to the forest-climate nexus along a "vertical" dimension across scales from global to local, addressing the biophysical interactions between forests and the atmosphere implies expansion across a "horizontal" dimension as well. In light of the science illuminating the effects of such interactions, the implications of forest cover change for climate stability can no longer be the sole purview of forest sector managers and climate policymakers. As illustrated in Figure 6.1, closing current policy gaps to prevent and address the full range of impacts of forest cover change on climate stability requires expanding consideration of the issues into sectoral decision-making in such areas as water, agriculture, and public health.

As described in Chapter 5, agriculture agencies need to consider how the extensification of crop production at the expense of forests could lead to declines in productivity through increased exposure to extreme temperatures, which may also compound the effects of reduced rainfall. And agencies responsible for public health and worker safety need to address the increased risk of heat stress faced by outdoor employees due to deforestation. While not explored in this report, agencies responsible for managing hydroelectric power installations, irrigation systems, and municipal water services that depend on rainfed reservoirs need to pay attention to the increased risk of drought due to upwind forest cover change (not just on upland watersheds, as they have increasingly recognized in many areas of the world). And engineers responsible for maintaining public infrastructure and private physical assets need to pay attention to the potential effects of increased temperature extremes due to deforestation on, for example, maintenance of rural roads. A comprehensive list of possible examples would be extensive.

As a result, recognition of the effects of deforestation on the local climate creates an additional imperative to break down silos between mitigation and adaptation measures, and among sectoral policy agendas in the context of national and local government agencies, as well as within the international donor agencies that support them. Bilateral and multilateral development agencies could provide incentives and support to countries to stimulate the full recognition and incorporation of forests' climate benefits into climate mitigation and adaptation strategies, agriculture and land-use planning, water and food security objectives, strategies to protect public health and worker safety, etc., to maximize the benefits forests provide to people.

> **Policies need to address both prevention of the loss of moisture and temperature regulation from forests' biophysical effects, as well as adaptation to the loss of such benefits, in order to optimize among alternative actions and investments.**

The IPCC Special Report on Global Warming of 1.5°C made clear that aggressive GHG emissions abatement is necessary across all sectors to have a chance of meeting the goals of the Paris Agreement, and that the world is already committed to significant warming in this century that will require extensive adaptation measures. Targeting limited political attention and financial resources to the most effective, efficient, and equitable climate actions is thus imperative.

We recognize that the history of climate policy suggests a reluctance to expand its scope due to fears that such expansion would create moral hazard by lessening the pressure on GHG emissions abatement. Such reluctance was once applied to investment in adaptation measures commensurate with investment in mitigation measures. Currently, research into solar radiation management (SRM) and its underlying physical processes has been viewed by many as taboo due to a fear that even discussing SRM as an option could reduce collective efforts to reduce GHG emissions. And the recent fanfare over "nature-based solutions" (NbS) has been rejected by some as a diversion from the imperative of phasing out fossil fuel emissions.

Nevertheless, the science summarized in this report suggests that the biophysical benefits from forests for both climate mitigation and adaptation are sufficiently significant to merit a place within the scope of relevant policy agendas. Those agendas include protection and restoration of forests to maintain and increase those benefits, as well as the development of policy approaches in other sectors to address the adverse impacts of their loss, as described above. Only by considering the magnitude and distribution of these benefits—and of the costs of losing them—alongside other mitigation and adaptation options will we be able to make the best policy choices. Such consideration will in turn depend on improved tracking at the national level to better understand and value the full suite of climate-regulation services—both GHG and not—that a country's forests and forest change are providing domestically and through global impacts, as well as on continued research to reduce remaining uncertainties.

> **While there is significant opportunity to integrate consideration of the biophysical benefits of forests into existing institutional mandates, it may also be necessary to create new institutions to fill gaps.**

Management of forests is implicated in the mandates of a wide range of government agencies and multistakeholder policy processes across scales. As a result, in addition to the selected examples covered in Chapters 3, 4, and 5, there are many opportunities to advance this set of issues. At the international level, several non-climate policy arenas may provide appropriate forums. For example, global agenda-setting instruments, such as the Sustainable Development Goals, include both forest and climate objectives and may provide a venue for drawing attention to biophysical forest-climate interactions. The forest restoration agenda, including the current UN Decade on Ecosystem Restoration and the Bonn Challenge, is a second opportunity. The geographic variation in countries with forest restoration commitments—including tropical as well as temperate and boreal zone countries—might suggest the value of a quantitative assessment of the biophysical global climate impacts of Bonn Challenge commitments.

In other cases, it might be necessary to create new institutions where the mandate or membership of existing forums proves too limiting. For example, it might be appropriate to include the effects of forest cover change on albedo under the umbrella of a new institution to govern SRM, as described in Chapter 3. And as described in Chapter 4, institutional innovation may be needed to address the transboundary impacts of deforestation on rainfall.

LOOKING AHEAD

We conclude by looking ahead, and identifying frontiers of further action by scientists, policymakers, and other stakeholders not explored in this report.

While much of what we know about the biophysical processes through which forests affect climate stability is well-established science, appreciation of their combined significance by the broader scientific community is relatively recent, and very new to policymakers and other audiences. Most of the relevant scientific literature on these topics was published since 2000, and much of it since 2010. As a result, in addition to outreach to policymakers regarding policy implications, an early task is one of disseminating this knowledge to scientists specializing in related fields and encouraging the funding of further research to fill in remaining gaps and uncertainties.

In addition, to translate the science into metrics meaningful to decision-making, further research is needed to quantify the economic and financial impacts of the biophysical effects of forest loss. An understanding of the magnitude and spatial extent of biophysical impacts is a precondition for estimating their economic impacts, which remain almost entirely unexplored. The relationships among the biophysical and economic variables are not simple or linear and can vary from one place to another depending on background climate and other factors. Due to the high degree of diversity of forests and the political systems that govern them, research on both biophysical risks and feasible responses will need to be contextualized to national and local circumstances. Nevertheless, translating biophysical impacts into economic impacts is likely to be the most effective strategy for gaining the attention of policymakers.

A third frontier is bringing together policymakers with the scientists and economists who are advancing research such as that suggested above. This is obviously an area of action we have prioritized, as this report itself was a first attempt at identifying opportunities and venues for bringing the science of biophysical forest-climate impacts into relevant processes—which ideally would provide fodder for such convenings. But there is much more work to be done in this area. Policy-relevant scientific research advances most quickly when information flows in both directions: to help ensure that research is targeted to areas with significant potential policy impact, to learn from policy analogues, and to bring social scientists into these processes from the start (see, e.g., Fisher et al. 2020). In addition, such research should build on the traditional knowledge of Indigenous and local communities.

Fourth, exploring the implications of biophysical forest-climate interactions for private sector actors will be an important next step. The deforestation-induced climate instability described in this report, including exposure to erratic rainfall and extreme temperatures, poses risks to private investment. Corporate contributions toward and exposure to such risks are increasingly subject to disclosure requirements, for example, through such initiatives as the Task Force on Climate-Related Financial Disclosures and the Task Force on Nature-Related Financial Disclosures. With access to better spatial data and analysis of the impacts of land-use change, investors, financiers, and insurers could increasingly reward companies that do a better job of managing those risks—and appropriately value the risk exposure of those who do not.

This report has taken only the first step in identifying some of the most important policy implications of the multiple ways that forests affect climate stability beyond their role in the global carbon cycle. We hope that it succeeds in raising awareness of these additional forest-climate interactions and inspires further research and action to begin closing the many policy gaps that remain.

ABBREVIATIONS

ACT	Amazon Cooperation Treaty
ACTO	Amazon Cooperation Treaty Organization
AR6	Sixth Assessment Reports
BNDES	Brazilian Development Bank
BVOCs	Biogenic volatile organic compounds
CBFP	Congo Basin Forest Partnership
CDR	Carbon dioxide removal
COMIFAC	Central African Forest Commission
FAO	Food and Agriculture Organization
FAR	"First Assessment Report" (followed by the SAR, TAR, AR4, AR5, AR6...)
FOLU/AFOLU	Forestry and other land use / agriculture, forestry, and other land use
FREL	Forest Reference Emission Levels
GCM	General circulation model
GEF	Global Environment Facility
HWP	Harvested wood product
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated water resources management
LULUCF	Land Use, Land-Use Change, and Forestry
NAP	National Adaptation Plan
NBI	Nile Basin Initiative
NbS	Nature-based solution
NDC	Nationally Determined Contribution
NYDF	New York Declaration on Forests
PBAPs	Primary biological aerosol particles
PES	Payments for ecosystem services schemes
PPATS	Preventing Pandemics at the Source
PROFOR	Program on Forests (World Bank–managed)
REDD+	Reducing Emissions from Deforestation and forest Degradation plus conservation, sustainable management of forests, and enhancement of forest carbon stocks
SBSTA	Subsidiary Body for Scientific and Technical Advice
SDG	Sustainable Development Goal
SLCP	Short-lived climate pollutant
SOAs	Secondary organic aerosols
SRCCL	Special Report on Climate Change and Land
SRM	Solar radiation management
TMR	Terrestrial moisture recycling
UFRGS	Federal University of Rio Grande do Sul
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
UNSG	United Nations Secretary General
WCD	World Commission on Dams

GLOSSARY

Albedo: The proportion of sunlight (solar radiation) reflected by a surface or object, often expressed as a percentage (IPCC 2019a).

Anthropogenic: Referring to environmental change caused or influenced by people, either directly or indirectly (USGS 2015).

Background climate: The prevailing climate conditions in an area that don't depend on the ecosystem type found in that area.

Biogenic volatile organic compounds (BVOCs): Organic compounds emitted from terrestrial and aquatic ecosystems that are important in atmospheric chemistry as precursors for ozone and secondary organic aerosol formation (IPCC 2019a).

Biogeochemical mechanisms: Mechanisms related to the chemical, physical, geological, and biological processes and reactions that govern the composition and natural environment, in particular those related to cycles of carbon, nitrogen, phosphorus, and other elements that can influence climate.

Biophysical mechanisms: Mechanisms related to biologically mediated land-surface properties and exchanges, including albedo (or reflectivity), surface roughness, and evapotranspiration.

Black carbon: A particulate form of carbon that is released from the incomplete combustion of carbon-based fuels (Raga et al. 2018).

Cerrado: The largest savanna region in South America, located between the Amazon, Atlantic Forests, and Pantanal (WWF 2020).

Climate mainstreaming (climate policy integration): Integrating climate change objectives into sectoral policies (di Gregorio et al. 2016).

Cloud seeding: A weather modification tactic used to increase rainfall (Ellison et al. 2018).

Convection: Vertical motion driven by buoyancy forces arising from static instability, usually caused by near-surface warming or cloud-top radiative cooling in the case of the atmosphere (IPCC 2019a).

Double cropping: The process of growing two full crops per year on the same land (Elwin and Baldock 2021).

Edge effects: The results of the interaction between two adjacent ecosystems, when the two are separated by an abrupt transition (Murcia 1995).

Evaporation: The physical process by which a liquid (e.g., water) becomes a gas (e.g., water vapor) (IPCC 2019a).

Evaporationshed: Describes the downwind atmosphere and surface that receives precipitation from a specific location's evaporation (Van der Ent 2014).

Evapotranspiration: The combined processes through which water is transferred to the atmosphere, including physical evaporation from soil and vegetation and biological transpiration from vegetation.

Feedback cycles (positive/negative): An interaction in which a perturbation in one quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced (IPCC 2019a).

General circulation models (GCMs): Global, 3D computer models of the climate system that link the atmosphere, oceans, and land surface (Lawrence and Vandecar 2015).

Geoengineering: A process that blocks or reflects a small portion of incoming sunlight, cooling the planet and reducing global warming, through SRM or CDR (Reynolds 2019).

In situ: Used to specify experiments or measurements that are made in the same place as the change being observed or tested.

Isoprene: Hydrocarbon compound produced and emitted by some plants (Sharkey et al. 2008).

Jurisdictional approach: A suite of models that seek to align governments, businesses, nongovernmental organizations, local communities, and other stakeholders around common interests in conservation, supply chain sustainability, and green economic development (Fishman et al. 2017).

Latent heat: Energy required to exchange water from liquid to gas during evaporation (Spracklen et al. 2018).

Leaf area index: A measure of leaf surface area per unit of ground area and an important property of the land surface that modulates transfer of moisture to the atmosphere via transpiration (Spracklen et al. 2018).

Ozone: The triatomic form of oxygen and a gaseous atmospheric constituent (IPCC 2019a).

Payments for ecosystem services (PES) schemes: Voluntary and conditional transfers aimed at increasing environmental service provisions relative to a given baseline (Wunder and Borner 2012).

Precipitationshed: Defines a spatial boundary enclosing upwind evaporative sources of downwind precipitation (Keys et al. 2018).

Primary biological aerosol particles (PBAPs): Solid airborne particles derived from biological organisms, including bacteria, fungal spores, and pollen, which have various effects on atmospheric albedo and surface temperature.

Radiative forcing: The change in the net, downward minus upward, radiative flux (expressed in watts/m^2) due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide (CO_2), the concentration of volcanic aerosols, or in the output of the sun (IPCC 2019a).

Regional regulatory instruments: Regional policies and agreements used to regulate nations in a common geographic region.

Savannization: The transformation of forest to lower biomass savanna structure, associated with the emergence of fire in the system (Silvério et al. 2013).

Secondary organic aerosols (SOAs): Air pollutants emitted from natural and man-made sources that are produced through a complex interaction of sunlight, volatile organic compounds from trees, plants, cars or industrial emissions, and other airborne chemicals (U.S. EPA 2016).

Sensible heat: The energy required to change the temperature of a substance with no phase change (NCSU n.d.).

Sink: Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere (IPCC 2019a).

Solar radiation management (SRM): Refers to a set of potential responses to climate change that would operate by reflecting some amount of incoming solar energy back into space in a way that is not trapped by the gases that produce the greenhouse effect.

Source: Any process or activity that releases a greenhouse gas, an aerosol, or a precursor of a greenhouse gas into the atmosphere (IPCC 2019a).

Stratospheric aerosol injection: A solar radiation management proposal to spray large quantities of reflective particles into the stratosphere.

Surface roughness: Describes the efficiency of momentum transfer between the surface and atmosphere (Spracklen et al. 2018).

Terpenes: The most numerous and structurally diverse group of secondary metabolites produced by plants, built up from isoprene subunits (Bhadra et al. 2015).

Terrestrial moisture recycling (TMR): The land-based precipitation that comes from evaporation that originates from other land sources rather than over the ocean (Keys et al. 2017).

Transboundary water agreements: Treaties designed to govern internationally shared water sources (Giordano et al. 2014).

Transpiration: The transfer of water from soil to atmosphere through plants.

Turbulence: Transfer of momentum and energy between the surface and atmosphere (Spracklen et al. 2018).

Uptake: The transfer of substances (such as carbon) or energy (e.g., heat) from one compartment of a system to another (IPCC 2019a).

Urban heat island effect: An increase in urban air temperature as compared to surrounding suburban and rural temperature due to naturally vegetated surfaces—for example, grass and trees—being replaced with nonreflective, water-resistant, impervious surfaces that absorb a high percentage of incoming solar radiation (Rosenzweig et al. 2006).

ENDNOTES

1. We use the term *carbon emissions* when methane is or may be included alongside CO_2 or in reference to the global carbon cycle, and the term *GHG emissions* when comparing forest emissions to broader emissions categories or as a more general term that emphasizes the "greenhouse warming" role of CO_2 in particular.

2. The IPCC's Special Report on Climate Change and Land estimates that the natural response of land to human-induced environmental change is a sequestration of 11.2 (± 2.6) $GtCO_2$ per year average from 2007 to 2016, or ~29 percent of anthropogenic CO_2 emissions over the period (IPCC 2019b). The Sixth Assessment Report updates this estimate to 12.47 (± 3.3) $GtCO_2$ per year average from 2010 to 2019, or ~31 percent of anthropogenic CO_2 emissions over the period (Canadell et al. 2021).

3. Net AFOLU emissions averaged 12.0 ± 2.9 $GtCO_2eq$/year from 2007 to 2016. SRCCL Summary for Policy Makers A.3, p. 10, and Chapter 2, p. 133. The Working Group I contribution to the IPCC Sixth Assessment Report, currently approved and released subject to final copyediting and layout, does not provide directly comparable estimates of AFOLU emissions including CO_2, CH_4, and N_2O in CO_2-equivalents, apparently as a result of temporal misalignment between the most recent decadal estimates, and evolving understanding of the temporal dynamics of different climate forcers and decreasing reliance on using set Global Warming Potential (GWP) to estimate CO_2-equivalents.

4. Average annual net FOLU GHG emissions from 2007 to 2016 are estimated by the SRCCL to be 5.8 ± 2.6 $GtCO_2eq$/year or 11 percent of total GHGs, while average annual FOLU CO_2 emissions over the same period were estimated to be 5.2 ± 2.6 $GtCO_2$/year or 13 percent of total CO_2 (SRCCL SPM). Average annual net FOLU CO_2 emissions from 2010 to 2019 are estimated by the Working Group I of the AR6 to be 5.9 ± 2.6 Gt CO_2, or 14 percent of total CO_2 emissions.

5. "Cost-effective" mitigation is considered as $100/tons (t) CO_2 or less; "safeguarded" maximum estimates avoid negative overall impacts on biodiversity and food and fiber security, for example preventing reforestation of ecologically important grasslands or necessary agricultural lands.

6. Comparing the 1850–1900 average to 2006–15 average (IPCC 2019b, 42).

7. Because this report does not set out to be comprehensive, we set aside the question of potential docking points within the UNFCCC for addressing the impacts that forests can have on regional and subglobal climate patterns.

8. It is worth noting that forests are implicated in a wide range of international policy processes beyond the UNFCCC that may provide additional forums for advancing this set of issues. For example, global agenda-setting instruments, such as the Sustainable Development Goals, include both forest and climate objectives and may provide a venue for drawing attention to non-GHG forest-climate interactions. The forest restoration agenda and the Bonn Challenge could be a second opportunity.

9. The phrase "emissions abatement" here is used to mean reducing GHG emissions specifically. In common parlance, "mitigate" generally means to reduce the future scale of impacts—which contrasts with the term-of-art use of "mitigation" within the UNFCCC context to mean abatement specifically with respect to the atmospheric concentration of GHGs that are covered by the Convention. Actions to influence non-GHG processes could "mitigate" future climate changes in the common-parlance sense of reducing the future change in long-term averages and extremes of temperature and precipitation—without being "mitigation" in UNFCCC-speak.

10. This issue is quite distinct from the accuracy of country inventories compared to what the atmosphere sees—it is rather about the scope of what is reported (GHG emissions only, not other climate forcers), and how that scope introduces latitudinal biases in the forests' reported climate services vs. their actual climate services.

11. Article 5.1 is a call to all parties (not just developing country parties) to "take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases as referred to in Article 4, paragraph 1(d), of the Convention, including forests," while 5.2 incorporates REDD+ Frameworks as specifically relevant to such actions in developing countries and support for such action by other parties.

12. The authors are indebted to Jose Antonio Prado for this insight.

13. Calculated from per capita government expenditure data available from "Health Expenditure Profile—Indonesia" (WHO 2021), based on an estimate of Indonesia's population in 2019 available at World Population Prospects (UN DESA 2021).

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Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

OUR VISION

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

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