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Forests and Climate: Impacts, Mitigation, and Adaptation

Climate and Forests 2030

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CLIMATE AND FORESTS 2030: RESOURCES FOR FUNDERS

Background

The Climate and Land Use Alliance (CLUA), with the support of Meridian Institute, is exploring the integration of climate and land use with justice, equity, health, and economic recovery through Climate and Forests 2030: Resources for Funders. This focus is intended to inspire innovation and investment in integrated work on forests, rights, and sustainable land use and will inform a new strategic plan for CLUA for the period 2021 to 2030.

To inform the thinking, CLUA commissioned a series of "thought pieces" to provide diverse inputs into developing a more integrated approach for forests and land use. These are meant to stimulate discussion and debate and are not intended to reflect the views of CLUA, its member foundations, or Meridian Institute. The views expressed in this paper are those of the authors.

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Executive Summary

Protecting and restoring forests is essential for achieving both international climate goals and sustainable development goals. Forests are simultaneously at risk from climate change, contributing to climate change, and part of the solution to climate change.

Forest vulnerability to degradation and loss is related both to pressure from human impacts (mainly agricultural expansion, but also logging, mining, and infrastructure expansion) and, increasingly, to climate change impacts on forests.

Climate change impacts on forests are happening and will become more common in the coming decade. Drought- and heat-induced die off, increasing rates of disturbance, and other climate impacts on forests tend towards decreasing forest health globally. Higher levels of atmospheric CO_2 have provided fertilization effects, but the counteracting impacts of warming will increase in importance in the coming decade and beyond. The magnitude of climate change impacts on forests depends on broader climate action, but climate change impacts will represent an increasingly important dimension of forest status.

At the same time, forests contribute to climate change solutions. Climate change mitigation from forests comes from three main categories: (1) carbon uptake of forests that makes up the background terrestrial carbon sink, (2) avoiding emissions from deforestation and forest degradation, and (3) increasing forest carbon sequestration.

The background terrestrial sink, much of which comes from forests, is critical to protect by limiting warming and by avoiding deforestation and forest degradation. The threat of losses to this background sink is likely more consequential than potential managed gains in forest carbon sequestration.

Land use change emissions from deforestation and forest degradation represent a significant amount of global greenhouse gas emissions. International goals to slow, halt, and reverse forest loss have not been met.

In a Paris-consistent (warming of 1.5-2°C) future, there will still be widespread drought, heat-induced die off, and increased disturbance in forests globally, but risk of ecosystem transformation in forests due to climate change will be much less than in a future of continued high emissions, with warming of 3-4°C. For this Paris-consistent future, drastic reductions in land use change emissions will be necessary as well as continued and increased carbon sequestration in the land.

In a continued high emissions (warming of 3-4°C) future, there will be potentially catastrophic increases in drought and heat stress that will likely push some forested ecosystems beyond their tolerances. The ability of the terrestrial biosphere to sequester carbon may be reduced due to climate change impacts, and there will be major risks of reversals of previously increased forest carbon storage.

It is critical that climate change mitigation not become the sole driver of forest protection. Traditionally important drivers for action such as biodiversity conservation and local development outcomes will continue to be important drivers into the future. Forest protection and restoration can be meaningful and important even if they do not move the global needle on climate change. Forests have a critical role to play in climate change adaptation and sustainable development.

Forest interventions must balance multiple factors including mitigation potential, adaptation and development effects, ecosystem services, biodiversity, local livelihoods, and more. The details of this balancing will vary based on local characteristics, but managing with a sole focus on carbon is likely to come at the expense of these other co-existing priorities. Monitoring a broad array of outcomes, developing policy mechanisms that recognize a full suite of ecosystem services, and managing adaptively will help reduce the potential for adverse outcomes.

FIGURE 1. Summary of the report's key themes. *Forests are at risk from climate change; their degradation and loss contribute to climate change; and forest protection and restoration can contribute to climate change mitigation and adaptation.*

Introduction

Forests globally are at risk due to climate change and increasing human impacts, but forests are also a part of the solution to climate change. This report aims to synthesize the state of the science regarding the intersections of climate change impacts, mitigation, and adaptation in forested ecosystems over the next decade. We present a range of plausible futures and identify key uncertainties and levers for change with the goal of guiding future decision-making and investment.

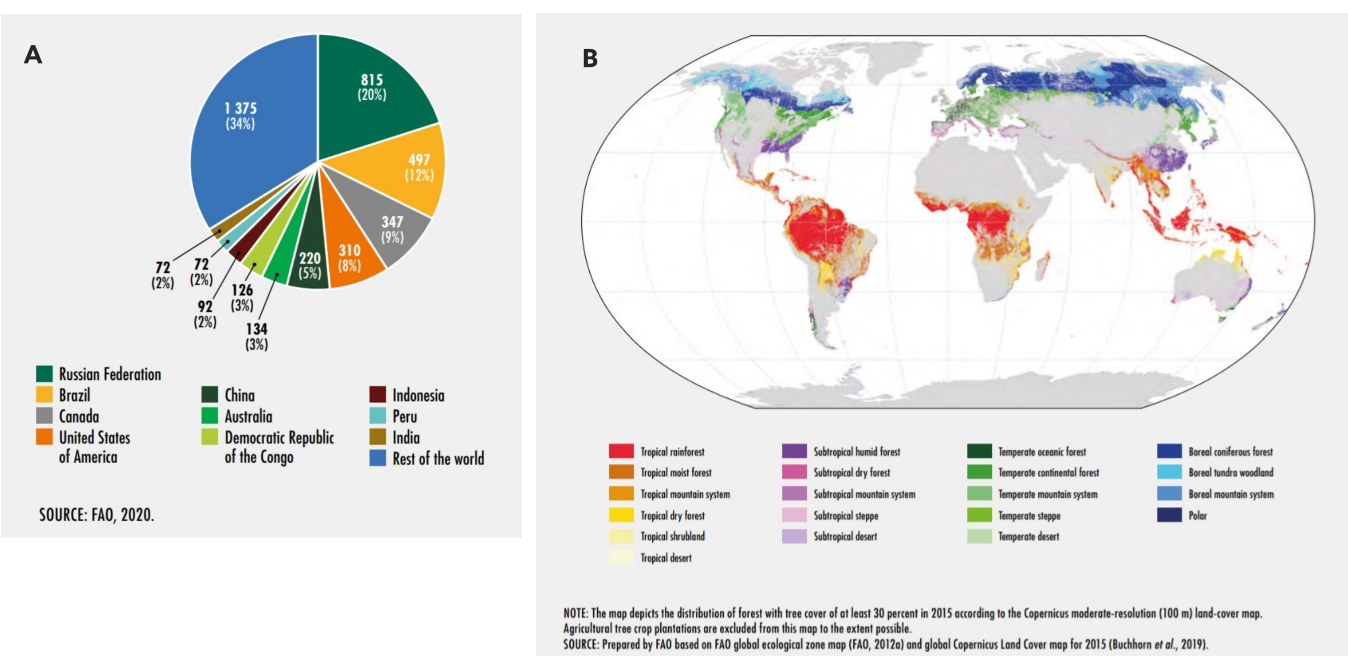
Forests are found on all vegetated continents and cover about 31% of global land area (FAO and UNEP 2020). Forests harbor most of Earth's terrestrial biodiversity: some 80% of all terrestrial plants and animals live in forests. Tropical moist forests alone contain half of the world's species richness in just 6-7% of the world's land area.

The majority of forest area is concentrated in just a few countries. Russia, Brazil, Canada, the United States, and China have more than half of the world's forest area (Figure 2A). Roughly 80% of the world's forest area is found in patches greater than 1 million hectares (10,000 km^2), but there are only 149 of these patches globally (Figure 2B). Conversely, 99.8% of all patches of forests (some 34.7 million patches) are less than 1,000 hectares (10 km^2).

Forests provide many ecosystem services, also known as nature's contributions to people. These contributions include provisioning services (e.g., providing food, freshwater, wood and fiber, or fuel); regulating services (e.g., pollination, water purification, or climate, disaster, and disease regulation); supporting services (e.g., nutrient cycling, soil formation, etc.); and cultural services (e.g., educational, aesthetic, and spiritual values, and recreation and tourism) (Millenium Ecosystem Assessment 2005). Recent analyses show that areas where people's needs for nature are greatest are often areas where nature's ability to meet those needs is declining, but sustainable development practices can reduce the threats posed by losses of nature (Chaplin-Kramer *et al.* 2019).

One of the most important ecosystem services that forests contribute globally is carbon sequestration. Forests are currently a large-scale effective climate solution. Each year the background land sink removes roughly 12 $GtCO_2y^{-1}$ (Friedlingstein *et al.* 2020). Forests are central to this background sink that

FIGURE 2. A. *From State of World's Forests 2020 (FAO and UNEP 2020), a pie chart showing the distribution of forested area. Roughly two-thirds of global forest area is in 10 countries.* **B.** *From State of World's Forests 2020: map of the most intact forests by global ecological zone. Figures reproduced under CC-BY-NC-SA 3.0 license.*



sequesters about 30% of annual anthropogenic CO_2 emissions.

Terrestrial vegetation stores more than 2,000 $GtCO_2e$. Land use change, mainly deforestation, emits significant amounts of CO_2. Some of the losses from deforestation are offset by regrowth on recently deforested land (Houghton 2020). Net land use change emissions are 5-6 $GtCO_2y^{-1}$, making up more than 10% of the roughly 40 $GtCO_2y^{-1}$ anthropogenic carbon dioxide emissions globally (Friedlingstein *et al*. 2020).

Maintaining and increasing natural carbon sequestration by protecting and expanding forests has the potential to be a powerful "win-win" that can help to achieve conservation, climate, and development goals simultaneously. While there is technical potential and these solutions are conceptually simple, implementation is complex. The potential for forests to contribute additional carbon dioxide removal has been known and discussed in the scientific literature for at least 30 years: a precursor to the Intergovernmental Panel on Climate Change (IPCC) published a report in 1990 estimating that restoring tropical forests could contribute cumulative negative emissions of 550 $GtCO_2$ (IPCC 1990). Since 2017, many new estimates for land management contributions to climate change mitigation (referred to as "natural climate solutions") have been published and received significant attention from NGOs, corporations, and governments, spurring action in the form of Trillion Tree campaigns and more (Griscom *et al*. 2017; Roe *et al*. 2019).

Forests contribute much more than just carbon sequestration. Everyone relies on forests, some people more directly than others. Forests contribute to livelihoods, food security, and health. Forests support livelihoods, agriculture, watersheds, and coastal protection, and help cities regulate temperature and water. There is a wide range of estimates for how many people globally are dependent on forests, but the best estimate is that roughly one-third of the world's 7.8 billion people have a close dependence on forests and forest products (FAO and UNEP 2020). This dependence involves living in forests and savannahs, using wood fuels for cooking and energy, practicing agroforestry, and practicing smallholder agriculture or forestry that relies heavily on the provisioning services of nearby forests. Additionally, vast amounts of wood products are produced and consumed every year.

Forests make many meaningful contributions to climate change adaptation and sustainable development that do not necessarily move the needle on climate (as measured by global carbon budgets, etc.). Despite the flurry of interest and investment in the carbon sequestration benefits of forests, non-carbon contributions have historically been and are likely to continue to be the most important near-term enablers for forest conservation and restoration.

Forest management choices do not occur in a vacuum. They are interconnected with agricultural systems, global population growth, climate action and policy, and more. This makes successfully leveraging forests to achieve climate change mitigation and adaptation goals more complicated than simply understanding the ecology of the system to make the most beneficial forest management choices. Overcoming challenges that extend into social, political, economic, and cultural domains can often be the biggest hurdle in implementing changes in forest management.

Despite the overall complexity of prioritizing competing interests, it is clear that forests and their incumbent biodiversity are critical for climate change adaptation and sustainable development. This means that solutions must be designed with multiple goals in mind and will require coordination and cross-cutting strategies to meet both biodiversity conservation and sustainable development goals. Degraded forests and forests impacted by climate change can have adverse adaptation effects. Therefore, a first step is to pursue a no-regrets strategy of reducing current threats to forests.

The decade from 2021 to 2030 will be critical for making meaningful progress on achieving international climate goals. 2021-2030 has been declared the UN Decade on Ecosystem Restoration. The initiative is "a rallying call for the protection and revival of ecosystems all around the world, for the benefit of people and nature." Restoration can contribute to climate action, but it is likely to contribute even more meaningfully to conservation of biodiversity and sustainable development.

Conceptually, the range of possibilities for forests over the next decade is large and contingent on forces both internal and external to forests. The next decade is critical for determining climate outcomes for the rest of this century. Much of this work will be outside the land sector: energy and transportation are dominant sources of anthropogenic greenhouse gas emissions. The 2020s could be defined by major progress towards reducing anthropogenic emissions to net zero on pathways consistent with limiting warming to 1.5 to 2°C and averting the worst impacts of climate change. In this optimistic world, protecting and expanding forest cover can be an excellent win-win-win, providing additional carbon sequestration and multiple co-benefits. Alternatively, the 2020s could be characterized by further delay and lock in peak warming more than 2°C. In this pessimistic world, the potential contribution of forests becomes significantly narrower, and investment in increasing forests may be at risk due to increased mortality, loss, and degradation from drought, heat, and disturbance. In a continued high emissions scenario, effort will have to be made to protect forests, ecosystem services, and the communities that rely on them.

In this report we focus on two main climate scenarios described above: (1) a below 2°C scenario consistent with the goals of the Paris Agreement under the United Nations Framework Convention on Climate Change, and (2) a 3-4°C continued high emissions scenario. For more information on future climate scenarios, Rogelj *et al.* (2018) provide an excellent overview of the climate change scenarios being used for IPCC Assessment Report 6. Possible climate futures range from 1.5°C to well over 4°C and everything in between, but a Paris-consistent and a continued high emissions scenario provide an envelope of plausible futures. We examine the different impacts and outcomes of each scenario in Figure 3. A key takeaway of this report is that forest investment strategies are contingent upon the investor's view of the overall climate trajectory.

FIGURE 3. Summary of the two scenarios discussed in this report and their associated impacts and opportunities.

	IMPACTS	OPPORTUNITIES
Continued high emissions (~3-4°C)	**SEVERE** Major climate and disturbance stresses on forests Risk of widespread ecosystem transformation globally Risk of loss of any additional carbon removals achieved via earlier actions	**LIMITED** Prioritize protection of existing forests Manage ecosystem transformation to minimize impacts to ecosystem services and the people who rely on them Targeted contributions to adaptation and sustainable development
Paris-consistent (~1.5-2°C)	**MODERATE** Continued and increased forest stress and disturbance Drought and heat-induced die off events continue on every vegetated continent Substantial range shifts with some risk of ecosystem transformations	**SIGNIFICANT** Ambitious forest protection and restoration simultaneously contributes to conservation, climate change mitigation, and sustainable development Forests continue to harbor biodiversity, store carbon, and provide a full suite of ecosystem services Land sharing approaches, such as agroforestry, can help protect both forests and livelihoods

We begin by discussing observed and projected climate change impacts on forests. Then, we discuss the role of forests in climate mitigation via both avoided emissions for deforestation and degradation and increasing forest carbon stocks by changes in management, regrowth and reforestation, and afforestation. Next, we briefly discuss the interconnections between forests and human adaptation to climate change and the ways that prioritizing carbon above all else can be potentially dangerous. Finally, we conclude by tying the sections together, noting challenges that span multiple domains.

Forests and climate interact at a wide range of spatial scales. Climate change impacts on forests span from global to regional and local. Forest-based climate change mitigation will be implemented at local scales, but the outcomes for climate are mainly at global scales. Gigatonne-scale carbon removal that moves the needle on global climate change requires large amounts of land and consideration of large-scale interactions that occur globally. The success of mitigation efforts is ultimately related to atmospheric greenhouse gas concentrations, an inherently global metric due to the well-mixed nature of the atmosphere. In contrast to the global scales of mitigation, forests also contribute to conservation, adaptation, and development at quite small spatial scales — the traditional key scale being the landscape. At the landscape scale, the question is how to make sure that everyone gets what they need without compromising the ability of the landscape to continue providing in the future.

Impacts of climate change on forests

KEY POINTS:

- Climate change impacts on forests, including drought and heat stress and die off and increases in disturbance, are happening now across all vegetated continents.
- Climate change impacts will continue and intensify in the future. More warming will lead to worse outcomes.
- Determining candidate areas for protection and restoration now requires careful consideration of present and future risk from climate change impacts.
- Warming, especially beyond 2°C, is likely to push some forested ecosystems beyond their physiological limits.
- Interventions to facilitate adaptation of forests or favorable transitions may be necessary to preserve ecosystem structure, composition, and function.

TAKE HOME MESSAGES: Climate change impacts on forests, including heat- and drought-induced die off and increases in disturbances, are happening and will increase in the coming decade. These impacts tend to decrease the amount of carbon stored on land — potentially offsetting or reversing the background sink. Under a continued high emissions scenario, widespread ecosystem transformation is likely.

IMPLICATION FOR INVESTMENTS: It is no longer sufficient to focus on human pressures on forests and simply account for land that has been set aside for conservation. Risks from climate change and its effects on forest quality must be considered. Climate change impacts could result in additional releases of carbon from forests and degradation or loss of key forest assets.

Climate change impacts on forests involve a combination of chronic drivers and transient impacts and their impacts on recruitment, growth, and mortality (McDowell *et al.*; Anderegg *et al.* 2020). The effects of climate change manifest both as changes in the chronic drivers (warmer conditions, higher atmospheric CO_2, longer growing seasons, altered precipitation) and as increasing frequency and severity of transient disturbances such as wildfire, drought, insect and disease outbreaks, and land use change. Climate change also affects precipitation patterns and growing season length, but these are secondary to the effects of temperature, CO_2, and disturbance (Williams *et al.* 2013; Zhang *et al.* 2021).

Effects of temperature and disturbance

Global mean surface temperatures have increased about 1°C from the preindustrial period (1850-1900) to present day (1999-2018). Temperature on the land surface has increased more than the global mean, by about 1.5°C. This warming has shifted climate zones poleward and toward higher elevations (Gonzalez *et al.* 2010). Climate change has also lengthened growing seasons and altered the phenology (timing of seasonal events) of ecosystems (Tang *et al.* 2016). Warming will continue and increase in the coming decade and beyond. These shifts mean that ecosystems will be exposed to temperatures to which they are not adapted and cannot readily adjust. This can result in changes of the composition, structure, and functioning of ecosystems. The timescale and spatial extent of temperature-related changes vary from region to region (IPCC 2019). Ecosystems have changed dramatically in response to past changes in climate over the past 20,000 years — changes that generally occurred much more gradually than modern ongoing changes. Most ecosystems globally are vulnerable to even moderate climate change (Settele *et al.* 2014; Nolan *et al.* 2018).

Drought- and heat-induced tree mortality has been documented on every vegetated continent (Allen *et al.* 2010). The balance of the evidence suggests major vulnerability to continued and increased drought- and heat-induced tree mortality (Allen *et al.* 2015). This greater vulnerability is suggested by a set of well-known, high confidence global drivers. Droughts occur everywhere (even in wet places); global warming is causing droughts that co-occur with warmer temperatures; vapor pressure deficit (atmospheric water demand, a key driver of mortality) increases nonlinearly with warming; tree death happens faster in hotter droughts; lethal droughts will become more frequent; and tree death happens much faster than forests are able to recover (Allen *et al.* 2015). Non-lethal drought and heat stress can make forests more vulnerable to attack by pests and pathogens (Anderegg *et al.* 2015).

Climate change impacts on ecosystems will tend to worsen as climate change increases. There are places where the 1°C warming we have experienced so far is already dangerous. There are other places that could be robust to significantly more warming. In general, limiting warming to 1.5°C will be better for ecosystems than 2°C; limiting warming to 2°C will be better than 3°C, and so on. The increase in impacts may not be linear, and the trajectories will vary from place to place. Tipping points and crossing of thresholds are possible especially as warming increases to well above 2°C (Steffen *et al.* 2018; Lenton *et al.* 2019).

Climate change impacts are happening in key geographies. Fires in California and Australia on scales that are beyond anything seen in the historical record have led to massive damage and wholesale transformation (Williams *et al.* 2019). Indonesian peat fires have led to major losses of carbon that may be irrecoverable (Heymann *et al.* 2017).

Amazon droughts in 2005, 2010, 2015, and 2016 were previously unprecedented in the historical record. These droughts have lasting effects on the Amazon's ability to store carbon. More frequent and severe droughts can reduce the Amazon's role as one of the most important contributors to the terrestrial carbon sink (Brienen *et al.* 2015; Yang *et al.* 2018).

While the next decade is critical for climate action, the climate changes and impacts between now and 2030 are already locked in. Droughts and heat waves will continue and intensify, leading to an increase in observed climate change impacts on forested ecosystems. The difference between ambitious mitigation and continued high emissions scenarios will happen after 2030 and will lead towards vastly different outcomes in the latter half of the 21st century and beyond.

Some ecosystems have already changed irreparably. Some ecosystems globally may be in a "zombie" state in which they are unable to re-establish in their current habitat because they are out of equilibrium with the current climate in their region. In these cases, the full extent of climate change impacts may not be seen until an ecosystem fails to recover after a disturbance.

Climate change impacts are already threatening biodiversity (IPBES 2019). Flexible biodiversity scenarios and goals will be necessary to account for the impacts of climate change on biodiversity (Arneth *et al.* 2020). Additionally, it is necessary to distinguish between ecosystem services provided by species, ecosystem services provided by ecosystems, and ecosystem services provided by landscapes — and necessary to encourage consideration of the varying impacts of management decisions at each of these scales. Adding these distinctions and lines of inquiry allows for nuanced decision-making regarding management interventions that maintain important ecosystem functioning.

Climate change also impacts disturbance patterns. Disturbances are a natural part of ecosystem dynamics and are critical for maintaining structure, composition, and function in many types of ecosystems, but climate change disrupts the equilibrium relationships between forests and disturbances. Fire seasons have lengthened, and fires have become more severe including in ecosystems where fire has traditionally not been a significant recurring disturbance.

Disturbance rate and forest biomass are closely interconnected (Bowman *et al.* 2020; Brando *et al.* 2014). Seemingly small changes in disturbance rates can have major impacts on forest biomass. For example, an increase in disturbance rate from 1% per year to 2% per year may not sound like a lot, but it would translate to a roughly 50% reduction in biomass. In many parts of the tropics, especially the Amazon and Congo Basins, the historic rate of stand replacing disturbance is extremely low, on the order of 0.01% per year or less (Anderegg *et al.* 2020; Pugh *et al.* 2019). In these systems then, there is a significant risk of drastic biomass reductions with nominally small increases in disturbance.

CO_2 concentration effects

Long-term changes in atmospheric CO_2 concentrations also impact ecosystems. Atmospheric CO_2 has risen from 280ppm in the pre-industrial period to more than 410ppm in 2020. Increases in atmospheric CO_2 increase leaf-scale photosynthesis and intrinsic water use efficiency (Walker *et al.* 2020). These direct responses sometimes lead to increased plant growth, biomass, and soil organic matter, which could ultimately increase the terrestrial carbon sink. In reality, ecosystem responses to elevated CO_2 will be complex and interact with other drivers of change. The balance of the evidence suggests that rising CO_2 accounts for some, but far from all, of the background terrestrial carbon sink (Walker *et al.* 2020). In the multi-stressor world, this will serve to slightly lessen the other impacts of climate change. Nutrient limitations, especially nitrogen and phosphorous, can limit the fertilization effect of increased atmospheric CO_2. (Peñuelas *et al.* 2017).

A recent analysis showed that the CO_2 fertilization effect declined from 1982 to 2015 across most of the globe. The decline seems to be linked to changing nutrient and soil water status (Wang *et al.* 2020). Ultimately, the strength of the CO_2 fertilization effect controls the ability of terrestrial ecosystems to provide a stabilizing feedback on global warming (Box 1).

Net climate change impacts

Models and past assessments have generally concluded that while the status of the terrestrial carbon uptake is uncertain, the land is likely to remain a significant sink over the next several decades regardless of the future scenario. These Earth system modeling results tend to neglect the potential for vegetation change and increases in disturbance because these are uncertain and difficult to model (Friedlingstein *et al.* 2014). Furthermore, as CO_2 increases slow, growth of net primary productivity will also slow, leading to decreases in carbon sequestration (Tokarska and Zickfeld 2015).

The balance of climate change impacts tends strongly toward impacts that decrease forest biomass (Baccini *et al.* 2017; Hubau *et al.* 2020). Currently, the balance of impacts has been a slight increase in carbon storage due to CO_2 fertilization that has been tempered by temperature stress effects. But there is significant evidence that ecosystems globally are likely to switch from a fertilization-dominated period to a warming-stress dominated mode (Peñuelas *et al.* 2017). Increased temperature stress, more frequent and more severe disturbance, and the general loss of large, old trees

BOX 1. The irony of carbon cycle feedbacks

Carbon cycle feedbacks are critical in determining the ultimate magnitude of climate change impacts. The degree to which carbon cycle feedbacks will modulate outcomes is a key unknown, but their directionality is known.

If we fail to control climate change there is a greater risk of carbon releases from the land and ocean that would worsen climate change impacts, potentially resulting in extreme warming outcomes.

On the other hand, if we are successful at rapidly reducing greenhouse gas emissions, the CO_2 fertilization effect that has increased carbon sequestration on land will slow, and with that, the ability of the terrestrial biosphere to sequester additional carbon will lessen. This suggests that the most consequential time to attempt to enhance land carbon sequestration is now, while CO_2 emissions are relatively high. A similar effort under lower CO_2 emissions will be less effective.

globally leads to younger, more stressed, and shorter statured ecosystems that are likely to store less carbon (McDowell *et al.* 2020).

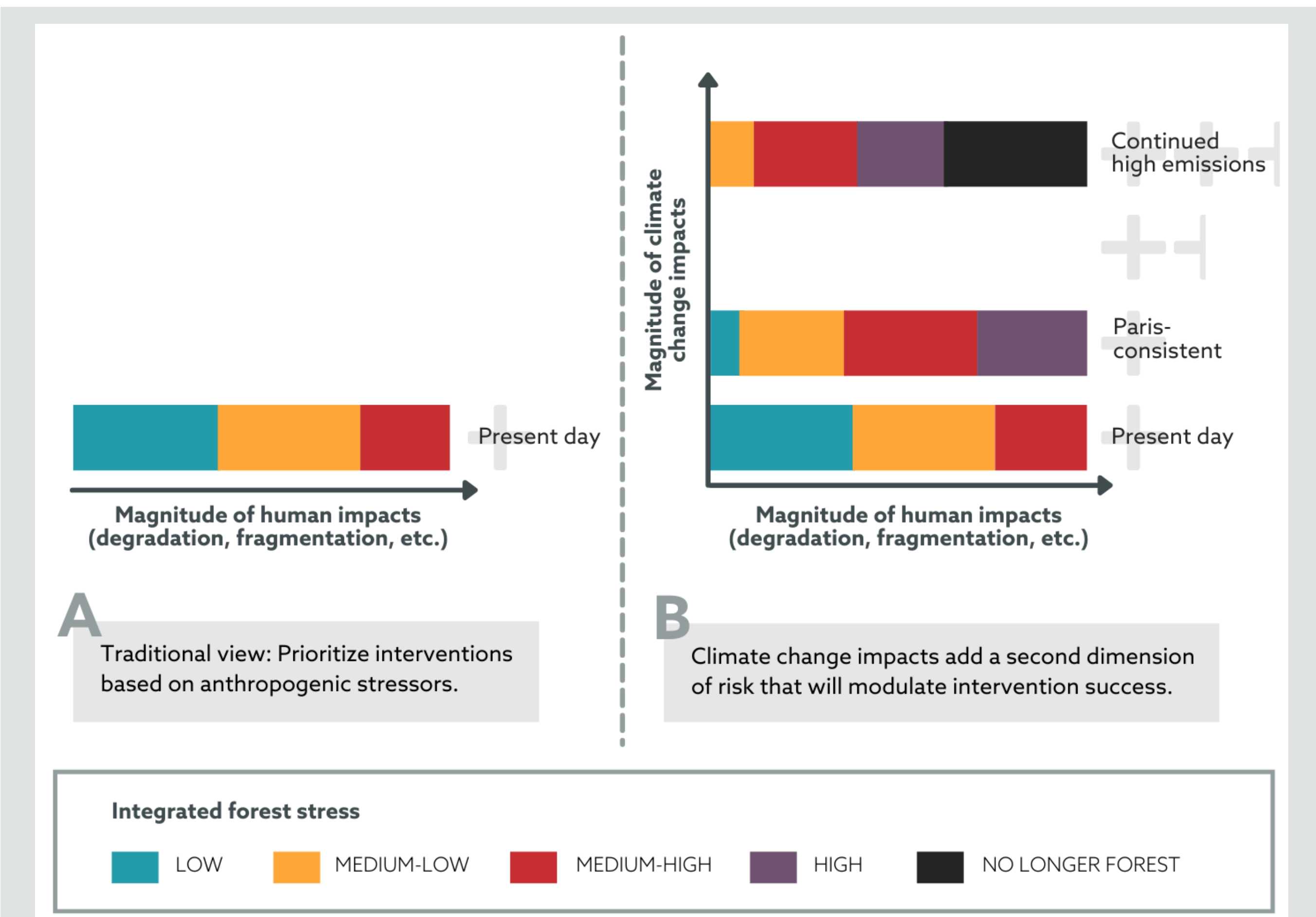
Assessing the impact of multiple stressors

Exposure to climate change impacts can be exacerbated by exposure to human impacts, especially forest fragmentation. Understanding the intersection of multiple stressors is a critical part of understanding where certain interventions are likely to be successful and where investment should be prioritized.

Climate stress, then, is emerging as a new dimension of forest vulnerability (Figure 4). Traditionally forests are targeted for protection and restoration based on criteria that mainly consider human impacts and pressure such as effects of fragmentation, pressure from expanding agriculture, changes in accessibility, etc. These metrics will still be important to consider, but additional considerations related to risks from climate change impacts and associated increases in disturbance will need to be incorporated into decision-making frameworks.

Climate change impacts and human pressure can

FIGURE 4. *Conceptual representation of the dimensions of risk to forests. In the traditional view (**Panel A**), projects are prioritized based on human impacts and pressure on forests. As climate impacts have emerged and expand, risk to forests from climate change and associated changes (e.g., disturbance frequency and severity) adds a second dimension of impact (**Panel B**). Climate risk is modulated by scenario (1.5/2°C Paris consistent scenario vs. 3-4°C continued high emissions scenario) and by local levels of climate impact. Colors represent a spectrum from low integrated stress (blue) to higher (orange, red, purple). Low stress areas might be traditionally targeted for protection and conservation, but those measures may be ineffective in the face of additional stress from climate change. Higher stress areas may be targeted for restoration, but with the added impacts of climate change the integrated stress may be too much to overcome.*



interact to lead to worse outcomes. Degraded forests are less resilient to climate change impacts. Deforestation combined with climate change impacts can increase the likelihood of a step-change in ecosystem state. In this way, forest conservation and restoration are an important aspect of increasing the resiliency of forested ecosystems.

This new dimension adds considerable additional uncertainty because of the interacting impacts of climate and human pressure. The questions to ask are no longer simply whether to intervene or not to intervene in a given geography, but those questions now have an additional dimension related to the severity of climate change impacts that are happening and are expected in the future in a particular location. Local questions of intervention become tied up in difficult-to-resolve uncertainties about global climate scenarios.

Management interventions for climate change impacts

Monitoring for climate change impacts and vulnerability is a critical, "no-regrets" action for protecting ecosystems. The International Union for the Conservation of Nature (IUCN), long known for its work designating and protecting endangered species, has also begun to assess and monitor threatened ecosystems via the IUCN Red List of Ecosystems. The current assessments are available here.

Climate change impacts this decade are likely to be severe enough to require significant management interventions. Monitoring and management should especially seek to identify potential thresholds and ease transitions to minimize loss of ecosystem services in an emerging era of "megadisturbance" (Millar and Stephenson 2015). A wide range of interventions will be on the table including interventions that aim to maintain some ecosystems in their current place and form as well as interventions that facilitate transitions to new ecosystem states (Figure 5) (Locatelli *et al.* 2010).

Management interventions towards protecting ecosystems and increasing resilience include managing fuel loads, reducing the effects of invasive species, and active management after a disturbance. These can require a lot of effort and may be effective only in the short term, especially if climate change impacts continue and accelerate. It will be important to "learn-as-you-go" and consistently re-evaluate management actions based on changing conditions and the effectiveness of interventions (Millar *et al.* 2007).

Droughts and megadroughts have caused significant impacts on ecosystems, including ecosystem transformation (Godfree *et al.* 2019). Managing in response to drought impacts requires fine scale action. In cases of extreme drought, it may not be possible to protect an entire landscape, but it may be possible to maintain "refugia" that help ensure the continued survival of critical biodiversity. Other actions to manage ecosystems during drought include selective thinning, contouring of water flows, adding native seeds, amending the soil, and supplying supplemental irrigation (Field *et al.* 2020).

Under a continued high emissions scenario, widespread ecosystem transformation will be likely across large parts of the globe because the change in climate will push vegetation out of equilibrium with its local climate (Svenning and Sandel 2013). Climate change will happen too quickly for forests to migrate, especially given major habitat fragmentation globally, and the changes will be too great for forests to adapt in place.

In the face of nonstationary climate conditions and ecosystem transformation, a useful framework for management choices is to resist, accept, or direct the changes (Thompson *et al.* 2020). **Resisting change** involves efforts that maintain ecosystem structure, composition, or function consistent with historical or current conditions. This can be successful if the drivers causing the changes are expected to be limited in their magnitude or duration. **Accepting change** is simply allowing ecosystem transformation to a novel state relative to modern or historical conditions. **Directing change** is taking active measures to manage the transformation to a desired new state in a way that leads to improved outcomes relative to passively accepting the changes. These three categories (resist, accept, direct) encapsulate all possible responses to ecological change, though there are a range of potential implementation choices within each category.

The security of investments towards protecting forests from climate change impacts hinges on the scale of the impacts. Difficult choices about what to protect via which strategies will abound. In one strategy, protection could be focused on the ecosystems most at risk of rapid change in an effort to stabilize them and prevent degradation and loss. This is a high risk, but high reward strategy in that success would lead to the protection of at-risk ecosystems — but in the face of ongoing climate change, the efforts could be futile. In contrast, protection efforts could focus on ecosystems with relatively less exposure to climate change impacts that are thus more likely to be stable from changes. This strategy is more likely to lead to safe investments in forests but could fail to reach full potential for forests' contributions to conservation and climate change mitigation.

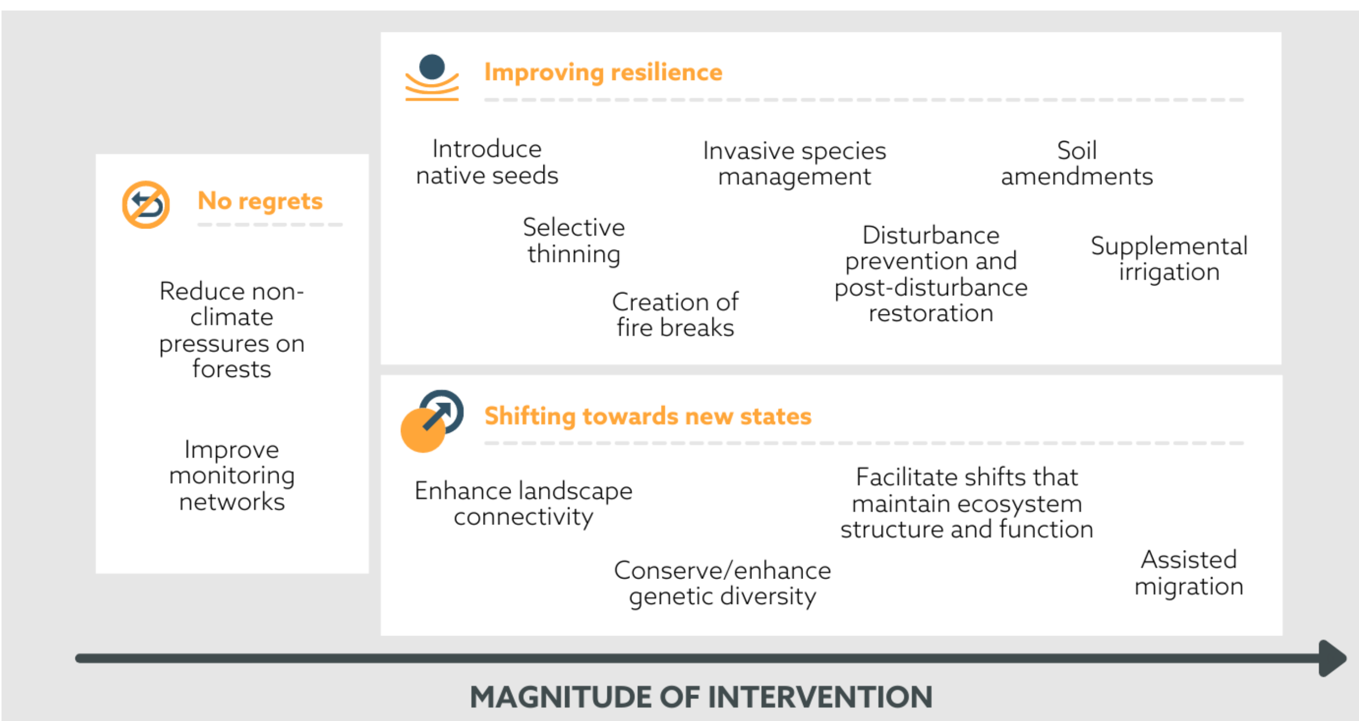
Management choices about protecting forests from climate change impacts also affect human adaptation and sustainable development outcomes. Loss of forests from disturbance and loss of ecosystem services from forests due to climate change impacts threaten local populations that rely on forests. Interventions to increase the resilience of forests and manage transitions in a way that maintains ecosystem services will lead to better adaptation and development outcomes. These interconnections will be critical to consider when managing for climate change impacts on forests.

Role of forests and land use in mitigation

KEY POINTS:

- Forests remove carbon from the atmosphere with their growth.
- Land use change, mainly deforestation and forest degradation, is a source of greenhouse gas emissions. There has been limited progress on international goals to slow, halt, and reverse forest cover and carbon loss.
- Ensuring continuation of the residual terrestrial sink and avoiding emissions from deforestation and forest degradation are important, high impact actions for forest-based climate mitigation.
- Limited increases in land-based carbon sequestration are possible, but other sources of negative emissions are likely to be necessary.
- Forest protection and restoration are valuable for conservation, adaptation, and sustainable development. Climate change mitigation must not bear the entirety of forest protection.

FIGURE 5. *Conceptual illustration of three main categories of management actions in response to climate change impacts on forests and the relative magnitude of management effort. With increased magnitude of interventions comes increased risk of unforeseen, adverse outcomes.*



TAKE HOME MESSAGES: Protecting existing carbon storage in the terrestrial biosphere by limiting warming and avoiding deforestation and degradation is critical and likely more effective than managed attempts to increase carbon storage on land. Managing forests with a singular focus on carbon is likely to lead to negative outcomes.

IMPLICATION FOR INVESTMENTS: Protecting forests and ensuring the land's ongoing contribution to carbon removal are likely less expensive, less risky, and more impactful than attempting to increase carbon storage in the terrestrial biosphere, but they are potentially more difficult to finance given market realities. Investments in increased carbon removal must consider the risks of reversals and ensure that they are resilient to climate change impacts and actually result in new reductions in atmospheric CO_2.

Climate change mitigation is defined by the IPCC as "a human intervention to reduce emissions or enhance sinks of greenhouse gases." Since forests are both a source of greenhouse gas emissions and a greenhouse gas sink, forest-based actions can contribute to mitigation of climate change in multiple ways. In this section, we focus on the direct contributions of forests to climate change mitigation, via avoided emissions and increased removals with a carbon-centric focus.

Carbon sequestration in the land sector is confusingly accounted for both in the background terrestrial land sink and in net land use change emissions (Houghton 2020). Regrowth and reforestation after recent deforestation is accounted for in the net land use change emissions whereas regrowth not associated with recent deforestation is accounted for in the background sink (Pugh *et al.* 2019).

Climate change mitigation from forests can then come from at least three different sources: (1) unmanaged natural carbon sequestration that makes up the background terrestrial land sink, (2) reducing land use change emissions from deforestation and forest degradation, and (3) increasing land management-based carbon sequestration.

Background terrestrial sink

The background terrestrial land sink is often calculated as the difference between CO_2 emissions (both fossil fuel and land use change) and atmospheric CO_2 concentrations measured via air sampling plus the oceanic CO_2 sink. The background land sink is the most uncertain of the Earth's carbon sinks because it cannot be directly measured; instead it is modeled with dynamic global vegetation models and calculated via the residuals in the global carbon budget. In recent years, the land sink has been around 12 $GtCO_2$ per year, or about 30% of CO_2 emissions (Friedlingstein *et al.* 2020).

The background land sink is mainly concentrated in intact and interior forests. It is highly variable year to year and especially sensitive to precipitation trends in important regions. The Amazon drought of 2005 reduced carbon storage over multiple years during and following the drought, resulting in a total reduction of more than 10 $GtCO_2$ (Yang *et al.* 2018). Semi-arid ecosystems can also contribute to increases in the terrestrial land sink during particularly wet years; 2011 in Australia is the primary example in recent years (Poulter *et al.* 2014). Year-to-year variations in the land sink are difficult to predict (Zscheischler *et al.* 2014).

The background land sink is treated inconsistently, if at all, in mitigation scenarios. Implicit or explicit assumptions that the land sink will continue as it has in the past are common. Protecting and maintaining the background land sink is an important and underappreciated aspect of climate change mitigation. These protections are in the public interest and are a thermodynamically favorable way to limit increases in atmospheric CO_2. However, these protections are difficult because they are not financially-lucrative in the same way that increasing sequestration may be. Policy frameworks make a necessary distinction between managed and unmanaged lands because protecting the unmanaged land sink does not and should not contribute carbon offsets for emissions elsewhere. But failure to protect the unmanaged land sink will result in worse climate change outcomes.

The main way to ensure the future of the land sink is to limit the warming from climate change — to ensure future functioning of ecosystems and their continued contribution to the land sink. Existing stocks can also be prioritized for protections by considering both biodiversity and intactness (FAO and UNEP 2020) and by protecting areas with "irrecoverable carbon" (Goldstein *et al.* 2020).

Reducing land use change

Land use change is a significant source of greenhouse gas emissions, and the main land use change is tropical deforestation. There is a hysteresis effect of deforestation in that the emission of carbon from land use change is fast and easy, whereas recovering that carbon is slow and difficult (Staal *et al.* 2020).

Agriculture remains the dominant driver of deforestation. Food production will need to increase by 50% by 2050 relative to 2013. Simply scaling up the current system would have major negative impacts on forests (FAO and UNEP 2020). Urban expansion and infrastructure also contribute. The main driver of forest degradation is livestock grazing in forests; fuelwood harvest, timber logging, and fires also contribute to degradation.

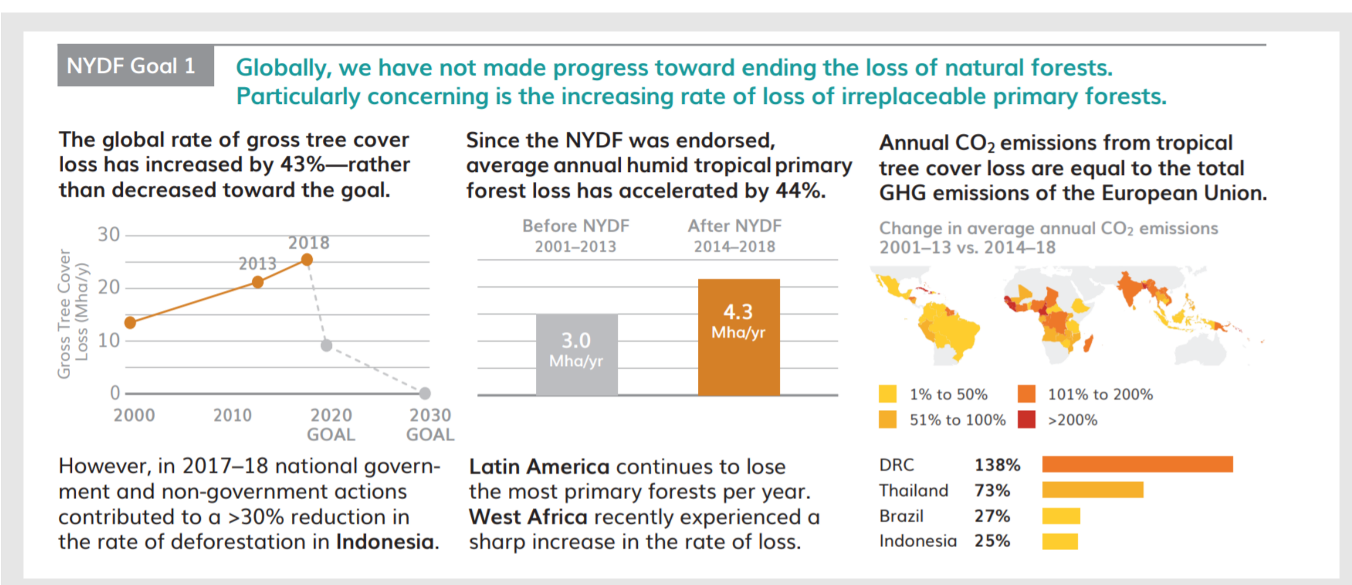
Deforestation has decreased from about 16 Mha per year in the 1990s to about 10 Mha per year from 2015 to 2020. The majority of the reductions came from South America, while deforestation in Africa has generally remained steady or increased. This reduction should be celebrated, but further progress is needed.

In 2014, the New York Declaration on Forests pledged to halve global forest cover loss by 2020 and reduce it to zero by 2030. A 2019 progress report showed that instead of a 50% decrease, there was a 43% increase in humid tropical tree cover loss (Figure 6) (NYDF Assessment Partners 2019).

The NYDF goals are consistent with UN Framework Convention on Climate Change calls to "slow, halt, and reverse forest cover and carbon loss." Slowing and ending deforestation are also central to the Sustainable Development Goals, in particular Goal 15 Life on Land to "[p]rotect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." The Bonn Challenge and the Aichi Biodiversity Targets also provide global commitments for forest restoration.

One of the main international programs from reducing deforestation is REDD+ ("reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries"). REDD+ was established under the Warsaw Framework in 2013. As of 2020, 50 countries have submitted a total of 60 forest reference (emissions) levels (FREL/FRLs) that collectively cover about one-third of global forested area and include countries responsible for three-quarters of global deforestation (FAO 2020). Thirteen countries have reported REDD+ results that total 9.03 $GtCO_2$. 90% of

FIGURE 6. *Deforestation progress and trends from the New York Declaration on Forests 2019 Five-Year Assessment Report (NYDF Assessment Partners 2019). Figure reproduced from Public Domain.*



the emissions reductions come from Brazil. As of 2020, the Green Climate Fund has approved results-based payments for six funding proposals (for Brazil, Chile, Colombia, Ecuador, Indonesia, and Paraguay) totaling 361 million USD.

The number of countries submitting FREL/FRLs and REDD+ results has been increasing in recent years will likely continue to increase over the next decade. Uganda is the first country in Africa to submit REDD+ results, and many African countries submitted their first FREL/FRLs in 2019 and 2020.

Jurisdictional REDD is a revised approach that seeks to act at the country or state level rather than the project level. The shift to the country level helps limit leakage and makes it easier to evaluate justice and equity outcomes (Wunder *et al.* 2020; Boyd *et al.* 2018). Alternatively, a carbon price, even a low carbon price, if it were to be implemented and enforced could drastically increase the cost of land clearance (Busch and Engelmann 2015).

Forest land management for climate change mitigation

Increasing land management-based carbon sequestration has come to prominence in recent years. These are often referred to as natural climate solutions (NCS), defined by Griscom *et al.* (2017) as "conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands." NCS include both avoided emissions and negative emissions (via increased carbon sequestration) from land management.

NCS interventions fall into three main categories: protect, manage, and restore (Figure 7). The "**protect**" category of interventions includes mainly avoided emissions from deforestation and forest degradation. Interventions in this category maintain carbon stocks in forests, but do not result in increases in carbon uptake and thus do not contribute to additional carbon dioxide sequestration or negative emissions. Avoiding deforestation and degradation is cost-effective, but durable climate change mitigation requires navigating persistent issues in forest-based climate change mitigation: leakage, additionality, and permanence (Box 2).

The "manage" and "restore" categories of NCS interventions do contribute to increased carbon dioxide sequestration. **Manage** entails improved forest management techniques such as lengthened rotation times and proforestation. **Restore** mainly

FIGURE 7. *Land management actions in forests that contribute to climate change mitigation generally fall into three categories: protecting land (for example, from deforestation or degradation), managing land for increased carbon storage, or restoring land. Numbers based on Roe* et al. in press.

	PROTECT	MANAGE	RESTORE
Example	Reduced deforestation	Sustainable forest management	Reforestation/ afforestation
Technical potential	~6 $GtCO_2$ /year	~2 $GtCO_2$ /year	~10 $GtCO_2$ /year
Cost-effective potential ($100 USD/$tCO_2$)	~4 $GtCO_2$ /year	~1 $GtCO_2$ /year	~1 $GtCO_2$ /year
Increased carbon sequestration?	No	Some	Yes

includes reforestation. Restoration interventions have a very large technical potential (~10 $GtCO_2$/year), but only a small fraction (~1 $GtCO_2$/year) is likely to be cost-effective at a price of \$100 tCO_2.

Many estimates for potential carbon sequestration gains from NCS have been published over recent years. The estimates have been difficult to compare directly because of different time scales, spatial scales, interventions considered, whether they offer only a rate, etc. We summarized more than 40 estimates and found that they vary widely from more than 1000 $GtCO_2$ to less than 100 $GtCO_2$ (see Figure 8).

Prominent NCS estimates in the literature are often focused on maximal rather than implementable potential. One particularly illustrative example is Bastin *et al.* (2019) which uses a machine learning approach to map areas that appear to be able to

BOX 2. Perennial issues in forest-based climate change mitigation

Leakage | Leakage is the idea that land protection, avoided impacts, and restoration in one location can often result in increased degradation or deforestation in another area. Leakage is a particularly thorny issue that is difficult to quantify, let alone avoid. The main problem is that policy boundaries are necessarily at the local, regional, and national levels, but in our globalized modern world avoided impacts on one continent can result in increased deforestation and degradation on another continent — thus the system boundaries rapidly expand to encompass the entire globe. This scale makes a comprehensive analysis all but impossible. Leakage is a particularly thorny problem because regions with the institutional stability to ensure sustainable use of forests are likely to be the same regions that are successful in reducing deforestation. Thus, if deforestation increases elsewhere it is more likely to be in an area where deforestation is done in more harmful ways.

Additionality | Additionality is the idea that in order to receive credit for climate mitigation a project must be proven to be above and beyond what would have happened in the absence of intervention. Additionality relies on unobservable counterfactuals and is thus difficult to prove. A move away from strict additionality requirements could remove some particularly difficult barriers for project approval and crediting and thus unleash additional funding streams, resulting in significantly more forest-based mitigation. It is likely that the overall increase in conservation efforts would significantly outweigh the minor projects that might not be "additional" by previous standards. To put it differently: strict additionality requirements are good at catching projects that do not meet additionality requirements, but they also hold up many desirable projects that are additional but are difficult to prove prior to implementation.

Permanence | Permanence is one of the most difficult and uncertain aspects of forest-based climate mitigation. In order for interventions to contribute positively to climate mitigation, they must be permanent on the order of 100+ years. The related challenges here are multiple and include costs and opportunity costs, monitoring and verification, effects of disturbance and climate change, stability of governance and sociopolitical institutions, and more. Risks from climate change and disturbance in offset programs are often managed by setting aside some of the carbon credits into a "buffer pool." Determining the appropriate size of the buffer pool is difficult. Buffer pools may be an inappropriate risk reduction mechanism in the face of nonstationary changes in disturbance, such as those projected in the coming decades if decarbonization and the scaling up of negative emissions technology do not accelerate quickly. In this case, it may become impossible to have a large enough insurance pool to account for losses in carbon from disturbance.

Leakage, additionality and permanence are all ultimately about how to ensure that carbon credits that get traded for forest protection and expansion actually lead to real changes in greenhouse gas emissions that are actually "felt" by the atmosphere. Ensuring that forest-based mitigation actually results in progress towards climate goals is a key concern. If the quality of forest-based carbon offsets is not prioritized, there is a significant risk for the industry to "race-to-the-bottom" and end up trading in low-quality offsets with significant issues. Ultimately, low quality carbon offsets may have detrimental effects on overall climate action. Even best quality carbon offsets have only a neutral effect on overall climate action.

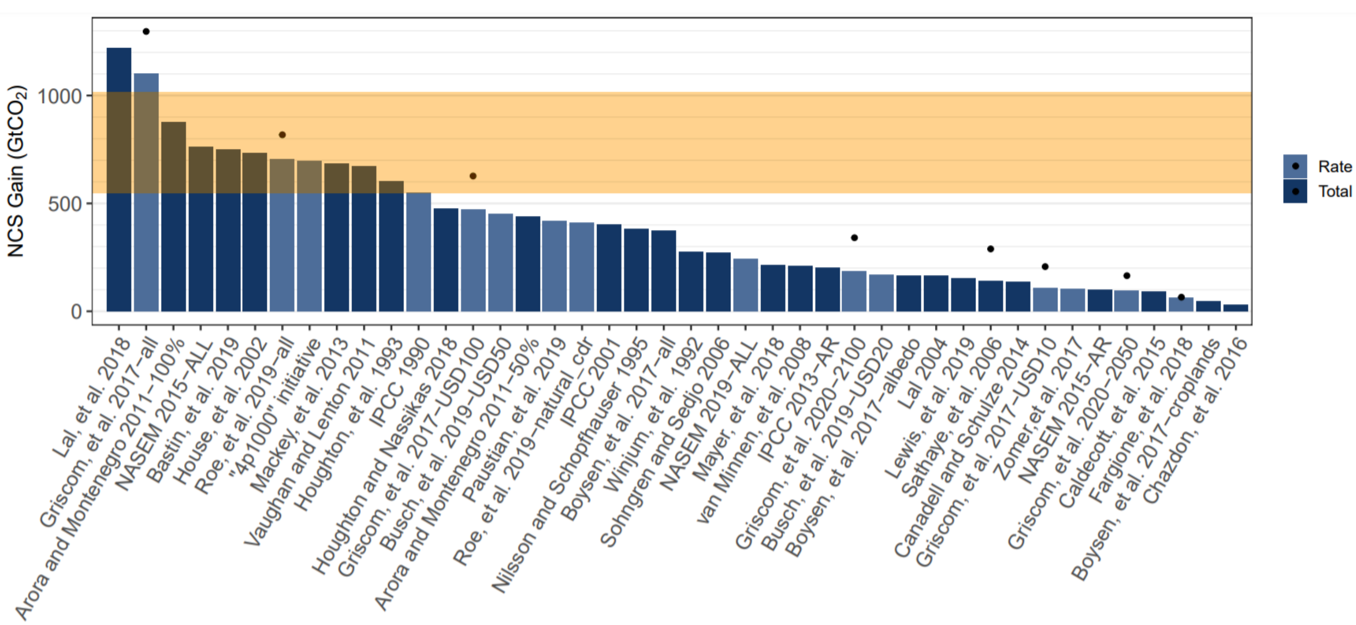
support additional forest cover. They find that there is an additional 1.7-1.8 Gha that could support forests, representing an additional 0.9 Gha of continuous canopy cover, and that would represent more than 700 $GtCO_2$ of additional carbon sequestration. This analysis is useful if it is recognized as a maximal estimate, but it is not implementable. The analysis does not consider the timescales that it would take to establish all of these new forests, the value of the existing vegetation and associated ecosystem services, the economic costs, the governance and sociopolitical challenges (e.g., land tenure), and more constraints that would limit the ability to expand the world's forest area by more than 50%.

Estimates that consider additional constraints such as economic costs, net climate effect, and land available generally find considerably lower estimates for potential additional sequestration (~200 $GtCO_2$ or less). A recent analysis of reforestation potential in Southeast Asia found that after accounting for economic and social constraints, only a fraction of the total mitigation potential was achievable (0.3-18%) (Zeng *et al.* 2020). Similar analyses in other regions would be beneficial for identifying realistic reforestation goals.

Griscom *et al.* (2020) analyzed strength of institutions and NCS potential relative to GDP in tropical countries. The main idea is that, in order to successfully implement NCS, countries need both stable institutions and money with which to do it. This paper identifies three main sets of countries: (1) countries with relatively stable institutions and potential for NCS that is doable for a small fraction of national GDP (for example, Indonesia, Brazil, and India); (2) countries with strong institutions but potential for NCS that is doable at a large fraction or a multiple of GDP (for example, Namibia, Guyana, Suriname, and the Solomon Islands); and (3) countries with relatively weak institutions and NCS that is costly relative to GDP (for example, the Democratic Republic of Congo, the Central African Republic, and Myanmar). Each of these different situations requires different international policy choices.

The stability of local and national institutions is central to forest-based climate change mitigation

FIGURE 8. *Estimates of carbon gain potential from natural climate solutions ordered by total or implied total additional carbon gain. Shading represents whether the estimate is a total carbon gain or a rate converted to an implied total. Carbon related to avoided deforestation was subtracted (the black dot represents the carbon storage with avoided deforestation included). The orange bar highlights the interquartile range of negative emissions needs through 2100 to limit global warming to 1.5°C in integrated assessment model scenarios. Figure from Nolan, Field, and Mach*in press.



success (Chazdon *et al.* 2020). For example, Brazil had seen significant success in reducing deforestation rates in the mid-2010s, but the trends reversed, and deforestation rates have increased again under the Bolsonaro regime. Thus, successful climate change mitigation from forests requires far more than just the biogeochemical potential to store carbon; the most difficult issues are often in policy and politics.

Financing

Leveraging financing for forest-based climate mitigation involves an interplay between public financing, private financing, and financing mechanisms. Success requires simultaneous progress on all three fronts. Financing mechanisms include international mechanisms such as REDD+, payment for ecosystem services schemes, and carbon markets. There is a significant amount of private finance that could be mobilized for forest NCS, but to overcome the risk aversion, arrangements that involve first losses going to public financing can be crucial. Furthermore, governmental investments in sophisticated measurement, reporting, and verification programs and the development of robust policy frameworks that provide confidence that there will be fair returns on investments can be important enablers for leveraging additional private financing.

Avoided emissions from deforestation and avoided forest degradation are commonly found in carbon offset markets. It is important to distinguish between avoided emissions and negative emissions (increased carbon sequestration). Newly developed Oxford Principles for Net Zero Offsetting provide valuable guidance to 1) follow existing best practice, 2) shift to carbon removal offsetting, 3) shift to long-lived storage, and 4) support the development of net zero-aligned offsetting (Allen *et al.* 2020). A recent analysis by carbonplan presents a permanence calculator and the idea of "renting" relatively cheap natural carbon storage for some period of time and then switching to permanent storage at some higher (but one-time) payment in the future, consistent with Oxford principle 3: the imperative to shift from short-lived to long-lived storage (carbonplan Team 2020).

Land requirements

Climate-relevant restoration requires a large amount of land. According to State of World's Forests 2020, there have been 170 Mha of land pledged for restoration, but since 2000, restoration has been done on only 26.5 Mha. By one recent estimate from the National Academy of Science, Engineering, and Medicine, achieving 1 $GtCO_2$ per year of afforestation/reforestation would require at least 70-90 Mha — a land area twice the size of California. Competition for land is likely to be intense between the need to feed a growing population, increased urbanization, and the potential for additional land-based negative emissions technologies such as bioenergy with carbon capture and storage.

Biophysical effects

Forests have significant biophysical effects, mainly related to their effects on surface reflectivity (albedo) and their effects on the water cycle through evapotranspiration. Afforestation and reforestation at mid to high latitudes, especially in boreal forest regions, can have adverse side effects of local warming that offset any potential global cooling effects via increased carbon sequestration. This local warming is caused by changes to Earth's surface reflectivity because forests absorb more sunlight than bare ground (especially snow-covered ground). In mid-to-high latitude forests this albedo effect makes reforestation and afforestation counterproductive. In tropical systems, the albedo effect and the carbon effect both work in the direction of cooler land surfaces, thus providing even more climatic cooling. In many systems, increased carbon sequestration comes at the cost of increased water use (Jackson *et al.* 2005). This can reduce streamflow and lead to soil degradation (via salination and acidification). The potential adverse water side effects must be considered in planning afforestation and reforestation projects.

Monitoring and assessing restoration success can be a key challenge. A recent report from the Food and Agriculture Organization (FAO) and World Resources Institute (WRI) provides guidelines for developing appropriate goals and metrics (FAO and WRI 2019). Appropriate monitoring depends on the goals, types of land use, and barriers to success. These then are targeted based on their priority level and the data that is available. Finally, all of this together yields a system of indicators and metrics for monitoring. Restoration is a process, not an end goal, and long-term outcomes depend on sustained effort.

BOX 3. Advances in measurement and modeling

The past decade has seen major advancements in measurement and monitoring of forest ecosystems and the carbon cycle.

Orbiting carbon observatory-2 (OCO-2) was launched in 2014 and provides space-based measurements of the column-averaged dry-air mole fraction of CO_2. OCO-2 provides net fluxes of CO_2. OCO-2 data has been used to estimate the emissions from the 2015 fires in Indonesia (Heymann *et al.* 2017). In general, though, OCO-2 is unable to resolve relative emissions versus sinks. OCO-3 was added to the International Space Station (ISS) in 2019. OCO-3 will have similar functionality to OCO-2, but with improved precision and OCO-3 will also be able to measure solar-induced fluorescence (SIF).

The ISS hosts a number of other relevant Earth observing missions including General Ecosystem Dynamics Investigation (GEDI) and Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2), which use LiDAR to measure forest structure, and Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), which uses a radiometer to investigate plant responses to drought and heat stress.

These missions, together with many more, represent a new level of detail in "top-down" measurements. Collectively, this has been called a "flux tower in the sky" (Schimel *et al.* 2019). These missions provide a level of detail into ecosystem responses to climate change, disturbance, and human pressure that was previously only available at a relatively small number of highly instrumented sites (Pastorello *et al.* 2017).

Global Forest Watch has compiled significant observation and monitoring resources into an easily accessible online platform. These data allow new scientific opportunities (e.g., a new accounting of forest carbon fluxes) and new opportunities for policy-relevant monitoring (Harris *et al.* 2021).

Reconciling top-down, global observations with bottom-up, site-specific measurements is a perennial issue in the global carbon cycle. A recent paper found that a new network of atmospheric CO_2 observations was important for refining carbon flux estimates in China (Wang *et al.* 2020). Improved networks of atmospheric CO_2 measurements in other parts of the world could yield similar improvements in estimates of ecosystem carbon flux.

BOX 4. Use of measurements in forest policy

Having reliable measurements is only one step in successfully deploying measurements for evaluation of forest climate mitigation. International climate policy must be applicable globally and consistently with currently available technology, and then it often takes years to implement.

Policies generally rely on an inventory approach that tracks the status of land and assigns standardized carbon values based on biome and status. IPCC inventory guidelines were developed in 2006 and then updated in 2019. These guidelines mostly do not take advantage of sophisticated measurement and monitoring developments described in Box 1.

A particularly difficult issue in policy frameworks is an unobservable counterfactual against which a mitigation intervention is compared. This is particularly salient for avoided emissions. A recent analysis showed that avoided deforestation projects in the Brazilian Amazon tended to overstate their emissions reductions (West *et al.* 2020).

Incorporating more sophisticated methods for measurement, reporting, and verification into international policy frameworks should be a priority in the coming decade. Doing so would help ensure the quality and integrity of nature-based carbon removal.

Interactions between impacts and mitigation

Beyond this wide range of additional constraints, the ultimate ability for forests to contribute to climate change mitigation is also dependent on broader climate change action (Figure 9). In a Paris-consistent future, ambitious forest interventions could provide significant mitigation and adaptation benefits (Locatelli *et al.* 2015). But in a continued high emissions world, high ambition forest interventions could end up being counterproductive if the forests are unable to withstand climate change impacts. More modest and targeted forest interventions can provide narrow contributions to mitigation and adaptation regardless of scenario.

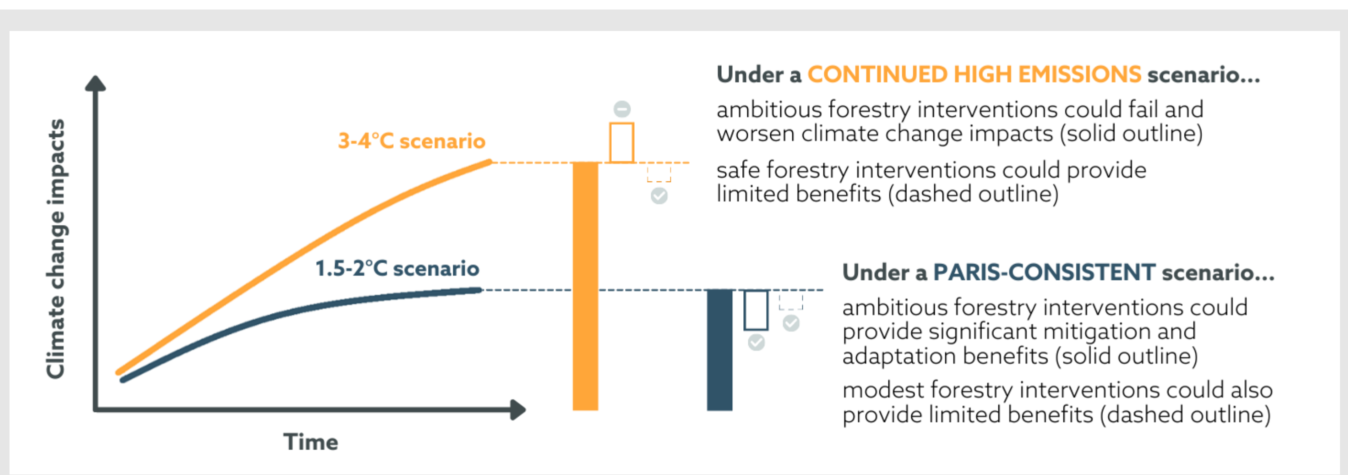
Furthermore, since climate change impacts tend to result in a reduction in forest biomass, even protected forests may store less carbon than historical baselines that are used to credit the interventions. This could lead to difficult questions about how to deal with natural variability and disturbance. There are incentives to want credit for natural variability that leads to increases in carbon storage and to be absolved of natural losses of carbon storage (e.g., from fire, pest/pathogen, or other disturbances) (Kurz *et al.* 2008). This creates a potential scenario where there is a consistent gap between the carbon credited and the changes in atmospheric CO_2.

Beyond climate mitigation

Forests and their incumbent biodiversity are critical for climate change adaptation and sustainable development (IPBES 2019). This means that solutions must be designed with multiple goals in mind and will require coordination and cross-cutting strategies to meet both biodiversity conservation and sustainable development goals. Degraded forests and forests impacted by climate change can have adverse adaptation effects. Therefore, a first step is to pursue a no-regrets strategy of reducing current threats to forests.

While forests can make meaningful contributions to climate change mitigation, it is also important not to put the entire burden of forest protection on mitigation. Effective forest management for the future will recognize and incorporate the full range of forest ecosystem services to provide adaptation and sustainable development (and potentially even more benefits from farther afield, such as pandemic prevention) (Dobson *et al.* 2020). Climate change mitigation can also help directly facilitate adaptation. Funding based on avoided emissions or additional carbon sequestration can provide a path for financing an adaptation project that also contributes some mitigation. This is because in some cases it can be easier to get financing for projects based on perceived global mitigation benefits than for projects

FIGURE 9. Stylized illustration of the tight interconnection between overall climate action and forestry intervention success. *Ambitious forest NCS can be beneficial and contribute to a portfolio of action that limits climate change impacts. But forest NCS are a solution that is put at risk by the problem they are contributing to solve, so if temperatures increase well beyond 2°C, the ambitious forest NCS implementation can become a liability and ultimately release additional CO_2 if the forests are lost due to climate change impacts.*



based mainly on local benefits. A frontier in this space would be moving beyond carbon markets to multi-benefit markets that provide financing opportunities that explicitly consider the full range of benefits a project can provide (Locatelli *et al.* 2016).

Initially, there are likely to be many projects that simultaneously advance climate, conservation, and sustainable development goals. But inevitably, at some point, there will be trade-offs. If climate change mitigation prevails as a dominant factor in decision-making this is likely to lead to adverse outcomes for conservation, sustainable development, and environmental justice.

Well-planned and managed climate change mitigation via forests should also have adaptation co-benefits. For example, REDD+ and similar forests protection mechanisms can lead to increased forest resilience. This resilience can be related to maintenance of intact and interior forests and through reduction in forest fragmentation and other degradation. REDD+ funding can also positively influence livelihoods and community adaptation. This can be via the payments directly but also via increased local coordination and strengthening of institutions.

Ensuring opportunities and sustainable development for people who live in and near forests upon which they are directly reliant must be a priority. These forests cannot become solely carbon credits allowing license for countries and corporations (mainly in faraway, richer countries) to continue emitting greenhouse gases.

Managing with a sole focus on increasing carbon storage is likely to lead to adverse outcomes. These could include negative impacts on ecosystem services, biodiversity, and sustainable development. For example, there are marked differences between restoring natural forests with a diverse mix of species vs. plantations of one or a few species, managed for (occasional) timber harvest. The former would help achieve broader conservation goals but requires more coordination and international financing. On the other hand, a timber producing plantation does not contribute to conservation goals, but it could pay for itself and require less coordination to implement.

Forest protection can also interact positively with the protection of indigenous peoples. Nobre and Nobre (2018) propose an Amazonia Third Way that protects the Amazon forest as a working landscape for indigenous and traditional people and seeks to develop a biodiversity-driven green economy. This is in contrast to the "First Way" which involves large tracts set aside for conservation and the "Second Way" which would seek to allow "sustainable" agriculture, energy, and mining use of the Amazon. This would be a major undertaking, but even incremental progress towards a new biodiversity-based valuation and use of the Amazon could be transformative.

Managing and restoring forests synergistically with achieving sustainable development goals requires careful balancing of priorities. Some of these priorities are difficult to quantify and map spatially with current available data, making the balancing of interests even more difficult. A holistic approach that considers social, economic, and environmental goals simultaneously will lead to the best possible outcomes. Implementing such an approach requires spatially disaggregated social science data about local communities as a valuable service for optimal planning. Collecting these data may seem far afield from forests and climate change adaptation, but their availability can be a key enabler and as such conservation communities should contribute to the development of social science datasets.

It is important to educate mitigation stakeholders about adaptation outcomes and choices. Further research on the synergies and trade-offs between forest-based mitigation and adaptation is necessary (Buck *et al.* 2020). Many exemplary projects lie at the nexus of climate change mitigation, climate change adaptation, and sustainable development. Projects that emphasize climate change mitigation at the expense of adaptation and sustainable development will be significant sources of risk and should generally be avoided.

Restoration approaches can have a variety of goals. When implemented properly, restoration can restore habitats and ecosystem function, create jobs and income, and sequester additional carbon in biomass and soils. Integrating local adaptation in mitigation projects increases local legitimacy and focuses on direct local benefits. Many projects can have significant benefits without significantly changing the global carbon budget.

Conclusions

OVERALL THEMES:

- Forests are part of the problem of climate change, part of the solution to climate change, and at risk from climate change.
- Success of forestry interventions is contingent on broader climate action.
- There is a delicate balancing act between the many activities and services forested lands support; maximizing any single one outcome is likely to lead to adverse effects for other outcomes.

In this report we have summarized climate impacts on forests and the role of forests in climate change mitigation, climate change adaptation, and sustainable development focusing on the next decade from 2021 to 2030.

Climate change impacts on forests are happening and will worsen in the coming decade. Impacts from climate change now add an additional dimension of vulnerability to consider when prioritizing forestry projects. This means that even when forests are successfully restored or protected from human impacts, they may be vulnerable to climate change impacts that can degrade the forest or, in extreme cases and/or with unmitigated climate change, lead to ecosystem transformation. Future research funding priorities include monitoring climate change impacts on forests and quantifying the interacting risks from human pressure on forests and vulnerability to climate change impacts.

Intact forests that are relatively free from human pressure may become at risk of climate impacts due to climate change. Protecting these forests will require a new way of thinking about conservation. It will not be enough to simply designate conservation areas. For some highly valuable species or ecosystems, more extreme and potentially-risky interventions such as introducing additional genetic variability or even assisted migration may be necessary.

Forests contribute significant climate change mitigation via the background terrestrial sink. Maintaining this sink by rapidly decarbonizing and avoiding deforestation and forest degradation is likely the most consequential role of forests in climate change mitigation. Research priorities include improved understanding of the background land sink assumptions in Integrated Assessment Model (IAM) scenarios and how those compare to Earth system modeling results under various future climate change scenarios.

Forests can also contribute some additional carbon dioxide removal. This can be particularly meaningful in combination with an aggressive climate action regime globally. In the absence of 2°C ambition globally, increases in forest carbon storage could become a liability as climate change impacts on forests increase to untenable levels. Future research should evaluate implemented forest-based efforts to increase carbon sequestration with careful evaluation of outcomes and generalizable lessons for future implementation.

Most individual forest restoration and conservation projects will not be implemented at a scale large enough to, by themselves, significantly contribute to climate change mitigation, but they will still provide critical and valuable adaptation and sustainable development gains. In these projects, identifying additional multidimensional metrics for prioritization will also be beneficial. These could include biodiversity and intactness (for identifying conservation priorities), forest cover and poverty (for predicting the success of the impacts of different payment approaches), and more. Some of these comparisons are limited by the availability of disaggregated social science data; investment in data collection and/or preparation could improve CLUA's ability to identify priority projects.

The decade from 2021 to 2030 is an important decade for climate action. Forests will play a key role in contributing to climate change mitigation, adaptation, and sustainable development. But simultaneously, forests are at risk from climate change impacts. The overall climate trajectory influences forest investment strategy for the next decade. It will be important to manage risks by envisioning what could go wrong with a given forest-based investment strategy if we end up on a continued high emissions trajectory. Furthermore, given the complex and interconnected problems, policy frameworks and decision-making must be flexible and adaptable to respond to unexpected outcomes from both the physical environment and sociopolitical spheres.

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