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Targeting climate finance for global forests

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Comprehensive data on costs of mitigation are needed to guide the scale and distribution of climate finance to sectors and regions where it will be most cost effective. We estimate the finance required to meet regional forest-based mitigation targets, aggregated from Nationally Determined Contributions (NDCs). Regions accounting for 70% of global forest carbon can meet their forest-based NDCs with carbon prices below \$100/tonne CO_2. The total investment required to meet regional targets is \$20-72 billion per year by 2030. Under a global coordination scenario, in which the same level of finance is available, but mitigation takes place where it is least costly, we project twice as much mitigation in 2030 as in the upper bound NDC scenario, at the same cost. This highlights potential cost savings from increasing mitigation in regions with low-cost mitigation potential that is not reflected in current national commitments and informs the next generation of NDCs.

Avoiding forest conversion, restoring degraded and deforested landscapes, and improving forest management are critical to limiting global climate change. These and other land-based mitigation activities have the potential to achieve up to one-third of the cost-effective mitigation needed to limit warming to 1.5 °C[1,2].

Abatement activities in forest ecosystems are also prominent components of climate change mitigation strategies proposed by individual countries[3,4]. More than 100 countries representing at least 90% of global forest cover explicitly include mitigation from forests in their nationally determined contributions (NDCs)[5].

Estimates of the potential mitigation from these forest-based components of NDCs range from 0.9–3.8 Gt CO_2 in 2030[3,4,6]. Importantly, these estimates do not account for market dynamics such as competition for land or forest product price effects, which can significantly influence the total cost of achieving these targets, and therefore their likelihood of attainment[7]. Models that represent these market and land dynamics are essential for estimating the scale of economically feasible mitigation opportunities[8].

The current scale of climate finance for forests, estimated at \$2.3 billion annually[9], is at least an order of magnitude smaller than what is needed to achieve mitigation compatible with a 1.5 °C pathway[10,11]. Climate finance broadly refers to funding from public, private, or other sources, used to support climate change mitigation or adaptation actions[12,13]. It can take forms ranging from alignment of public expenditures with climate targets, such as subsidy reform, increases in public funding such as domestic budget allocations and bilateral or multilateral finance, and mobilization of private finance via mechanisms such as carbon pricing or climate risk disclosure[14].

This study uses an economic model of global forests, the Global Timber Model (GTM)[11,15], to assess the level of finance needed to achieve forest-based NDC goals across 16 global regions. We project regional forest carbon fluxes in 2030 using GTM across a set of finance scenarios, represented using a theoretical carbon pricing mechanism, and considering future market conditions and biophysical characteristics of regional forests. We use these projections to estimate the cost of meeting regional forest-based NDC targets submitted to the United Nations Framework Convention on Climate Change (UNFCCC) between 2015–2021[4,16].

We compare the cost of achieving regional forest-based NDCs to a Global Coordination scenario in which the same level of climate finance is available for forests, but without requiring regional forest NDC targets to be met. This allows us to assess the efficiency of the NDC targets relative to a theoretically optimal allocation of mitigation action, and indicates cost-efficient opportunities for bridging gap between current NDCs and critical climate targets[17].

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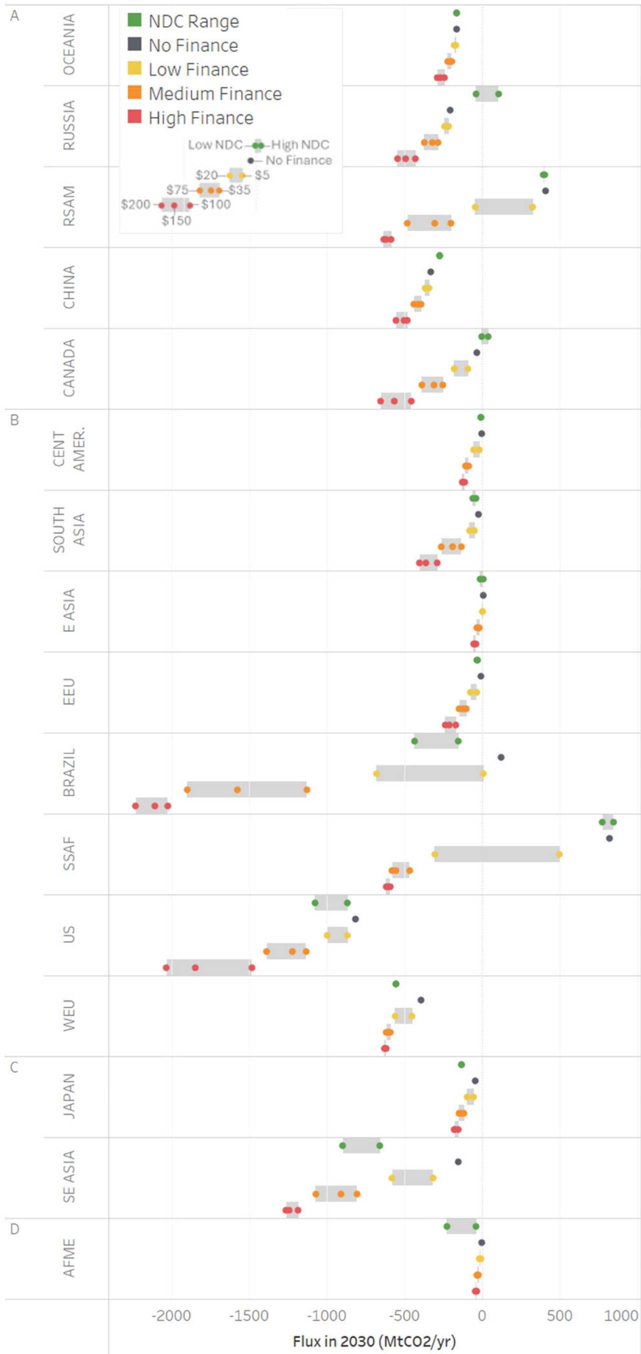

Fig. 1 | Regional net forest CO_2 flux in 2030 based on reported NDCs, compared to projected net flux under alternative finance scenarios. Regional net forest CO2 flux in 2030 based on reported NDCs is shown in green, with the range representing the NDC lower and upper bounds. This is compared to the projected net CO_2 flux under in the GTM baseline (no finance scenario, shown in blue) and under low (<\$20/ton CO_2, shown in yellow) medium (\$35/ton CO_2–75/ton CO_2, shown in orange), and high (> \$100/ton CO_2, shown in red) climate finance ranges. Regions are grouped by the estimated level of investment needed to achieve their aggregate forest-based NDC target, with regions in group A achieving their target without additional price incentives, group B achieving their target with low price incentives, group C achieving their targets with medium price incentives, and group D achieving their targets with high prices incentives. *Notes:* In the figure RSAM refers to South America not including Brazil, SSAF to Sub-Saharan Africa, EEU to Eastern Europe, WEU to Western Europe, and AFME to North Africa and the Middle East. Positive values indicate net emissions from forests while negative values represent net sequestration from forests.

These findings provide valuable input for countries in the process of updating their NDCs under the Global Stocktake process of the Paris Agreement, which calls for both periodic strengthening of existing NDC commitments and commitment to future mitigation targets[18]. This study also informs strategies for scaling high-quality climate finance, including building on the current commitmentof \$300 billion annually, agreed to at the 29th conference of Parties to the UNFCCC, to a target of \$1.3 trillion by 2035 to support developing countries' mitigation needs[19].

Results

The GTM projects that global forests will act as a net carbon sink of 0.8 Gt CO_2/yr in 2030 in the absence of climate finance. If countries achieve their NDC targets, this sink will increase to 1.5–2.8 Gt CO_2/yr in 2030, resulting in mitigation of 0.7–1.9 Gt CO_2 relative to the reference case.

We estimate that China, Russia, Canada, and Oceania can achieve their forest-based NDC targets without the need for additional climate finance (Group A in Fig. 1). The forests in these regions were a net sink of CO_2 in 2020[20,21], and GTM projects that the strength of this sink will increase through 2030 even in the absence of climate finance. This trend is due to projected changes in land use and management, including future increases in global demand for timber. In response to these demand signals, Russia and Oceania are projected to intensify forest management, China to continue expanding forest area, and Canada to pursue both strategies.

In 2020 the forests in South America not including Brazil were a net source of emissions, and under the region's aggregate NDC target, emissions from forests will continue to increase in line with the projected baseline without climate finance. Likewise, Sub-Saharan Africa's lower bound NDC commitment reflects a continuation of net emissions from forests, which GTM projects will continue without climate finance.

On the other hand, low levels of investment are needed to meet forest-based NDC targets in Central America, Brazil, Southeast Asia, South Asia, Europe and the U.S., in line with a carbon price of \$20/ton CO_2, as well as Sub-Saharan Africa's upper bound NDC target, in line with a carbon price of \$5/ton CO_2 (Group B in Fig. 1). In the absence of climate finance incentives, GTM projects the forests in these regions will either become a larger net source or a smaller net sink by 2030. Large opportunities for avoided deforestation in the tropics, and improved forest management in Europe, result in low-cost attainment of regional forest-based NDCs. In the U.S. additional investments in forest management, and reforestation in low-value agriculture land, can increase forest carbon in line with the nation's NDC[15].

Medium levels of investment are needed to reach forest-based NDC targets in East Asia and Japan (Group C in Fig. 1). Forests in Japan are projected to continue net sequestration even without direct investments, though carbon prices \$50/ton CO_2 are needed to increase sequestration sufficiently to meet the nation's NDC target. These relatively higher mitigation prices in Japan are due to its limited capacity to expand forest areas. Forests in East Asia are projected to become a net source of emissions by 2030, but with a carbon price of 35\$/ton CO_2 forests are projected become a net sink in line with the region's NDC target.

GTM projects that the region combining northern and eastern Africa and the Middle East will maintain a small net sink in 2030 (Group D in Fig. 1). Reaching the regions' lower bound NDC target, which includes a large mitigation commitment from Ethiopia, is projected to require a carbon price of \$100/ton CO_2, and reaching the region's upper bound target requires a carbon price > \$200/ton CO_2.

We estimate that achieving regional forest-based NDC commitments globally requires between \$20 – 72 billion annually in 2030. This

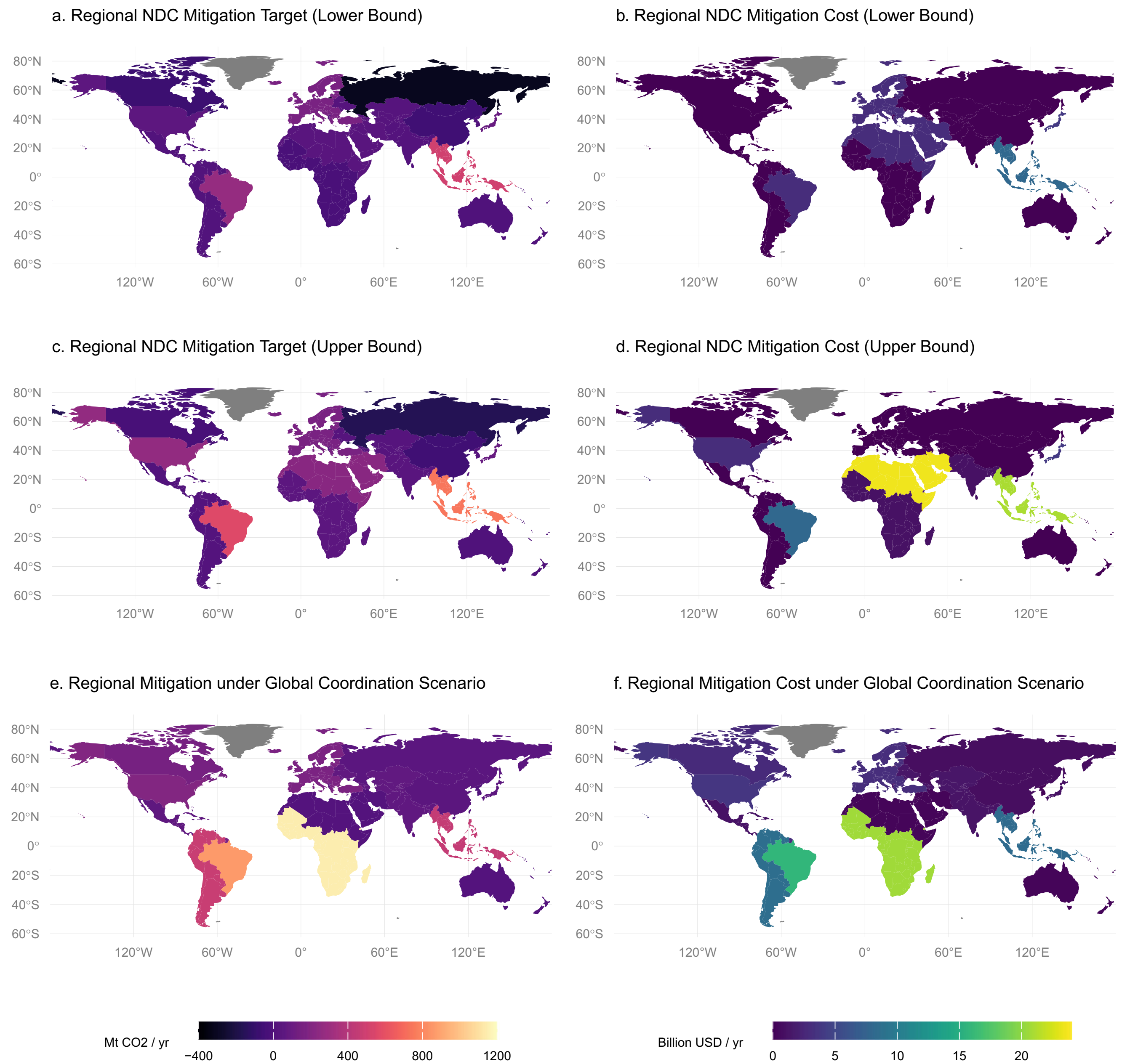

Fig. 2 | Costs and mitigation outcomes of meeting regional forest based NDCs, compared to a Global Coordination scenario, in 2030. Mitigation under lower bound Nationally Determined Contribution (NDC) targets (**a**), cost of reaching lower bound NDC targets (**b**), mitigation under upper bound NDC target (**c**), cost of reaching upper bound NDC targets (**d**), mitigation under a Global Coordination scenario (**e**), and cost of reaching the Global Coordination scenario mitigation quantity (**f**). We developed this figure using R version 4.4.3[59] and the rnaturalearth, ggplot2, and the viridis packages[60–62].

assumes that the region comprised of northern and eastern Africa and the Middle east could meet its upper bound NDC target at a carbon price of 200$/ton CO_2. Southeast Asia, Brazil, and Northern Africa and the Middle East together comprise 67–87% of total finance needed to reach all NDC targets (Fig. 2). On the other hand, due to the small differences between regional NDC targets and baseline forest carbon flux projections in Canada, Russia, China, South America outside Brazil, Oceania these regions do not require additional climate finance to reach their NDC targets.

We compare the costs of achieving regional NDC targets to a Global Coordination scenario, in which the same level of total global climate finance is made available as is required to meet the upper bound NDC target, but without requirements as to where mitigation occurs. To do so, we simulated two global carbon prices of $20/ton CO_2 and $35/ton CO_2 and interpolated between these scenarios to determine the carbon price that would result in the same quantity of investment needed to achieve this upper bound NDC target ($72 billion annually in 2030). Under this Global Coordination scenario, total mitigation from forests reaches 3.8 Gt CO_2, or twice the quantity of mitigation expected under the achievement of upper bound NDC commitments (1.9 Gt CO_2), at a carbon price of ~$22/ton CO_2.

These cost efficiencies are the product of a geographic shift in mitigation under the Global Coordination scenario, with large increases in low-cost mitigation in some regions, and slight decreases in very high-cost mitigation in other regions, relative to regional NDC targets (Fig. 2). Under the Global Coordination scenario, we project that Canada, Russia, China, Central America, and Oceania begin to take advantage of low-cost abatement opportunities that are not reflected in the in the first generation of their NDCs. Together, these five regions are projected to reach 0.3 Gt CO_2 of mitigation in 2030, requiring finance (either domestic, international or both) of $5 billion annually.

We also project substantially more mitigation in Sub Saharan Africa under the Global Coordination scenario, reaching net mitigation of 1.2 Gt CO_2 with climate finance of $21 Billion annually in 2030, Brazil, reaching 0.9 Gt CO_2 with climate finance of $16 Billion annually, and the rest of South America, reaching 0.5 Gt CO_2 with climate finance of $9 Billion annually. On the other hand, we project less mitigation in SE Asia, Japan, East Asia, Northern Africa and the Middle East, relative to these regions' aggregate NDC commitments, due to the comparatively higher cost of mitigation in these regions.

Importantly, ~0.5 Gt CO_2/ yr, or more than one-third, of Southeast Asia's emissions from land-use change are due to drainage and degradation of peat soils[22]. Reduction of emissions from peatlands are important components of the mitigation strategies of several countries in the region, including Indonesia[23]. The difference between Southeast Asia's upper bound mitigation commitment (0.7 Gt CO_2/ yr) and the estimate of regional mitigation under the Global coordination scenario (0.5 Gt CO_2/ yr) may be due to this large potential abatement opportunity in peatlands that is not reflected in GTM.

To assess the robustness of our findings, we examined the impacts of three alternative assumptions: slower forest growth due to absence of CO_2 fertilization, lower future increases in timber demand (10% lower relative to the main findings over 2025–2055), and slower increases in carbon prices (1% as opposed to 3% growth). Overall, the results presented in the paper are relatively insensitive to these alternative assumptions (Supplementary Fig. 1). This is due in large part to the time horizon of this study, as the anticipated impacts of these changes in carbon price growth, timber demand, and CO_2 fertilization are projected to manifest over many decades and have larger implications in mid-century and beyond.

We estimate that mitigation outcomes per dollar invested are most sensitive to assumptions about CO_2 fertilization. Under a globally coordinated $70 billion investment scenario, excluding assumptions of CO_2 fertilization leads to a 10% lower projection of global mitigation in 2030 (Figure S1, gray line). This result is expected, as investments that enhance forest productivity are aided by anticipated increases in tree growth due to CO_2 fertilization. In contrast, lowering global timber demand results in a 5% increase in projected mitigation per dollar invested under the $70 billion investment case in the short-term (Figure S1, yellow line). Finally, changes in future carbon prices have a negligible impact in the short term; under the same $70 billion scenario, results remain effectively unchanged (Figure S1, orange line). Price dynamics may play a more significant role in medium- to long-term projections by influencing forward-looking investment decisions.

Discussion

Our estimates of climate finance needed to realize forest-based NDC mitigation targets in 2030, of $20−$72 billion annually, are similar to previous estimates of finance needed to support forest and mitigation goals. These include estimates of $44–$210 billion annually needed for terrestrial protection and restoration by 2030[24], $45–$65 billion needed for protection and restoration of nature in 2030[25], and $19–$32 billion annually to transition forests currently managed for productive purposes to sustainable forestry practices[26]. Our upper bound mitigation cost estimate for the tropics is 12−16% of low- and middle-income countries' reported cross-sectoral climate finance needs of $455−584 billion annually by 2030 to implement NDCs[27].

This study makes two important advancements. First, we refine global scale analyses by estimating the distribution of finance needs needed to achieve regional forest-sector NDC targets. Overall, regions accounting for 70% of global forest carbon stocks can meet or exceed their forest-based NDC targets with carbon prices less than $100 / ton CO_2. Yet, on a regional basis, we observe large differences in the costs of meeting NDC targets. Regions with low-cost mitigation potential beyond what is reflected in current NDCs−including large opportunities in Sub-Saharan Africa, South America, China, Russia, and Canada −are priorities for closing the gap between what has been pledged under NDCs and what is needed to reach emissions compatible with a 1.5 °C pathway[28]. High income countries in this group can lead by adopting more stringent emissions reductions targets and expanding domestic investments in abatement in the forest sector.

Next, this study identifies potential cost efficiencies in global forest-based mitigation, by comparing mitigation achieved by meeting the upper bound NDC target (1.9 Gt CO_2) to mitigation achieved under a Global Coordination scenario (3.8 Gt CO_2). We project that this two-fold difference in mitigation can be achieved at no additional cost, due to lower projected mitigation in regions with high-cost abatement (e.g., Northern Africa and the Middle East), and higher projected mitigation in regions with low-cost abatement (e.g., Sub Saharan Africa), under the Global Coordination scenario. This finding is consistent with previous studies showing that a theoretical global carbon market could result in mitigation nearly double current cross-sectoral NDCs without increasing total costs, compared to a scenario without international markets[29], as well as previous research demonstrating theoretical cost-savings via international mitigation transfers[30–32].

Our assessment is constrained by a lack of clarity in forest-sector mitigation targets derived from the majority of NDC submissions. NDCs are widely acknowledged to be challenging to interpret given the broad diversity in how targets are articulated, the paucity of detail needed for clear interpretation, and large uncertainties with respect to the estimation and reporting of LULUCF fluxes generally[4,33,34]. Future iterations of NDC submissions are likely to have substantially improved clarity, facilitating improvements in these data inputs[35]. Notably, as the next generation of NDCs are announced and updated via the Global Stocktake process, and presentation of forest-specific detail is refined within these NDCs, the model outputs presented here can be used to assess cost and cost efficiencies[18,36].

The estimates of mitigation costs presented in this study are based on a model which simplifies reality in several ways. For instance, theoretical costs of mitigation are estimated under the assumption that a uniform price incentive on carbon is applied to all forest-based activities, and land managers act in the interest of optimizing their current and future welfare outcomes. These costs do not reflect transaction costs associated with developing and governing a high-integrity carbon market, building knowledge and capacity for participating in a market, or developing systems for monitoring, reporting and verifying carbon fluxes, which could be substantial[37]. In practice international cooperation may be carried out on a piecemeal basis, with domestic regulations on allowable credit purchases, bilateral arrangements that preference mitigation from certain geographies, or via public climate finance mechanisms that are not based solely on carbon pricing. Furthermore, there are non-monetary barriers to the adoption of mitigation activities in the land sector that are not accounted for in GTM and which can slow rates of adoption and behavior change needed to reach mitigation targets[38]. These include for example cultural preferences for established land use and production patterns, uncertainty around mitigation technologies or practices, or perceived volatility in carbon prices. These limitations are not unique to the GTM, and given the central role that this and other economic models play in the assessment of climate mitigation scenarios and the design of mitigation solutions, their continuous improvement merits attention and investment[39].

Despite these limitations, this study offers insights into the magnitude and distribution of finance needed to reach current forest-based NDC targets, as well as opportunities for efficient allocation of abatement to maximize mitigation per dollar invested via global coordination. As current cross-sectoral NDC pledges are likely to fall short of limiting warming to 1.5 °C (UNFCCC 2023), regional

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opportunities to cost-effectively increase forest-based mitigation, such as those highlighted here, are urgently needed.

The results presented here focus on short-term mitigation opportunities aligned with the 2030 NDC targets. A similar analysis could be extended to include medium- (2050) and long-term (2100) mitigation horizons, enabling evaluation of the cost efficiency of a broader set of national targets and informing their design and refinement. Indeed, near-term price signals may drive further action, particularly in forest management and afforestation/reforestation, leading to greater sequestration after 2030. This is especially important for forests, where the benefits of current investments take time to yield results.

Methods

Regional NDC targets

Nationally Determined Contributions (NDCs) are central components of the United Nations Framework Convention on Climate Change (UNFCCC). They are voluntary mitigation pledges made by individual countries which outline specific climate action towards mitigating climate change and adapting to its impacts, reflecting each country's circumstances, capabilities, and development priorities.

Countries representing at least 90% of global forest cover included land use, land cover change, and forestry (LULUCF) in their NDC submissions[5]. Countries formulated and reported their NDC targets using diverse approaches including variation in the articulation of targets (e.g., absolute quantities or change in emissions intensities), source and sink categories (e.g., forest definitions, activity definitions), reference points (e.g., relative to a historical year or relative to a projected baseline), and conditionality (e.g., whether financed domestically or requiring external support)[3,33,34,40]. Of the 121 countries with explicit LULUCF mitigation targets articulated in the first round of NDC submissions, just 11 provided quantitative detail such as a specific LULUCF reduction target, or specific LULUCF mitigation measures[5]. A 2024 assessment of updated NDCs reported that less than half of submissions include a quantitative forest-related emissions mitigation target[41].

This study uses estimates of LULUCF NDC targets for 44 countries[4,16], representing 84% of global forest cover[42] (Supplementary Table 1). Previous research examined the text of NDCs submitted to the UNFCCC and extracted LULUCF specific targets in 2030 where available. Where needed these studies carried out additional analyses and modeling to determine the LULUCF-specific contribution to a cross-sectoral NDC target. In some cases, NDC targets are presented as a range, reflecting uncertainty in the interpretation of the NDC and/or the difference between targets that are conditional or unconditional on international finance.

Most NDCs are not reported with sufficient detail to disaggregate mitigation targets from forests, wetlands, peatlands, grasslands, or soil carbon sequestration on agricultural lands[33,34]. We assumed that the mitigation needed to reach NDC targets is derived from forest-based activities including avoided deforestation, afforestation/ reforestation, and improved forest management. These activities comprise more than four-fifths of global land management mitigation potential, not including bioenergy with carbon capture and storage[1]. Low-cost mitigation opportunities from other ecosystems, such as peatlands and wetlands, are not represented in this study. Excluding these mitigation opportunities from our assessment may over-estimate mitigation costs, particularly in regions such as Southeast Asia where peatlands play an important role in the regional mitigation portfolio[43]. As NDC reporting transparency improves, future research may be able to differentiate mitigation targets, and improve estimates of mitigation costs, by ecosystem type[44].

Because GTM uses baseline greenhouse gas flux estimates calibrated to FAO reports[42], which differ from greenhouse gas inventory (GHGI) reported fluxes[45], we took steps to harmonize between the GHGI and GTM 2020 flux estimates. First, we calculated the difference between 2020 GHGI reported LULUCF fluxes and the 2030 country-reported NDC flux target (including upper and lower bounds, if provided as a range) for each country as follows:

$$Flux_{GHGI,2020} - Flux_{NDC,2030} = \Delta_{NDC,2030} \tag{1}$$

We used the resulting difference to represent the change required in GTM between 2020 and 2030 to achieve the NDC target, rather than requiring GTM to reach a specific flux value that may be misaligned with the FAO calibration data. Specifically, we calculated the 'target flux' as follows:

$$Flux_{GTM,2020} - \Delta_{NDC,2030} = TargetFlux_{GTM,2030} \tag{2}$$

We then summed national target fluxes within each of the sixteen regions represented in GTM, to report regional targets harmonized to GTM initial flux values (Supplementary Table 2). For countries that did not provide a LULUCF sector-specific target in their NDC, we assumed LULUCF emissions remain constant, neither contributing to nor detracting from the regional aggregate NDC target. This assumption may underestimate mitigation costs, as countries that did not provide a LULUCF target may still have low-cost forest-based mitigation opportunities represented in GTM that can 'contribute' to the regional mitigation target. However, given that the countries included in our assessment comprise 84% of global forest cover, the scale of underestimation due to regional aggregation is likely small.

The global timber model

This study used an economic model of the global forest sector, the Global Timber Model (GTM), to estimate mitigation quantities and costs under a reference scenario and under alternative scenarios representing varying levels of investments in forest-based mitigation activities. GTM has been used to project potential mitigation quantities and costs in several previous studies[11,15,46–48], and the model's data, parameters, carbon accounting procedures, and structural equations have been documented[49–51]. This study used a version of GTM including updates described in EPA (2024) and Favero et al.[15,48]. This includes updates to the initial stock of carbon for the US and Europe using more recent data for these regions, as well as updated land elasticity and agriculture productivity parameters, which are likely to affect the costs of converting land to forestland.

GTM integrates data on forest inventories, management approaches, and land management costs into an economic model that then projects harvest age and quantity, forest investment expenditure, and forest area, given both projected demand for wood products as well as carbon incentives[49].

GTM represents 350 different forest types in 16 global regions. The model differentiates forest resources by ecological productivity, as well as management and cost characteristics. To represent differences in productivity, different land classes across the 16 regions have different yield functions for timber, based on inventory data for each forest type and region. The model also discriminates forest management classes for forests:

1. Moderately valued forests, which are managed in rotations and located primarily in temperate regions.
2. Natural inaccessible forests, located in landscapes that are costly to access and to manage for timber production.
3. Low-value semi-accessible forests located in temperate and boreal areas that are lightly managed, if they are managed at all. These low-value forests are linked to inaccessible forests; when inaccessible forests are harvested in boreal and temperate zones, they are converted to semi-accessible forests.
4. Low-value timberland in inaccessible and semi-accessible regions of the tropics.

5. High-value intensively managed timber plantations. These plantations occur in the United States, South America, southern Africa, the Iberian Peninsula, Indonesia, and Oceania.

GTM operates by maximizing the net present value of consumers' and producers' surplus in the forestry sector. By doing so, the model optimizes the age of harvesting timber a and the intensity of regenerating and managing forests m_t^i. This is an optimal control problem given the starting stock, costs, and growth functions of forest stands, as well as the aggregate demand function. GTM relies on forward-looking behavior and solves all time periods at the same time. In other words, when land owners make decisions about forest management, they consider the implications of their decision on forests in the future with complete information. The result is a forecast of how a competitive market would impact forests.

Mathematically, this optimization problem is written formally as:

$$\max \sum_0^{\infty} \rho^t \left\{ \begin{array}{c} \int_0^{Q_t^{ind}} \left\{ D\left(Q_t^{ind}, Z_t\right) - C\left(Q_t^{tot}\right) \right\} dQ_t^{ind} - \\ \sum_i C_G^i\left(m_t^i, G_t^i\right) - \sum_i C_N^i\left(m_t^i, N_t^i\right) - \sum_i R_t^i\left(\sum_a X_{a,t}^i\right) + CarbInv_t \end{array} \right\} \quad (3)$$

In Eq., (3) ρ^t is a discount factor, $D\left(Q_t^{ind}, Z_t\right)$ is a global demand function for industrial wood products given the quantity of wood Q_t^{ind} and average global consumption per capita Z_t[52].

Industrial timber demand follows the general functional form $Q_t^{ind} = A_t\left(Z_t\right)^{\alpha} P_t^{\omega}$, where A_t is a constant, α is income elasticity, P_t is the timber price, and ω is price elasticity. The global demand function is for industrial round wood, which is an input into products like lumber, paper, plywood, lumber, and other manufactured wood products.

The version of GTM that we use in this study represents demand for sawtimber and pulpwood. We assume an international market for timber across the 16 regions leads to a global market clearing price. $C\left(Q_t^{tot}\right)$ is the cost function for harvesting and transporting logs to a mill or power plant for each type of timber, while $C_G^i(\cdot)$, is the cost function for planting land in temperate and previously inaccessible forests and $C_N^i(\cdot)$ is the cost function for planting forests in subtropical plantations.

GTM represents competition for land between the forestry sector and agriculture and pasture land using a rental supply function $R_t^i(\cdot)$ in Eq. 3. These land supply functions are unique to each region, reflecting variable biophysical and economic characteristics. With a price incentive on carbon, the value of land storing more carbon increases relative to land storing less carbon, driving new land to be converted to forests. The total amount of forest cover is therefore endogenous in the model. Importantly, this rental supply function is constrained to land that is naturally suitable for forests. GTM further assumes that the least productive crop- and pasture- land will be prioritized for conversion to forests, and that that rental rates increase as more land is converted to forests and thus becomes scarcer.

The total quantity of harvested wood depends upon the area of land harvested in the timber types in i for each age a and time t ($H_{a,t}^i$) and the yield function ($V_{a,t}^i$) which is itself a function of ecological forest productivity θ_t^i - which varies across regions following the expected changes under the RCP 4.5 - and management intensity m_{t0}^i (Eq. 4)

$$Q_t^{tot} = \sum_i \left(\sum_a H_{a,t}^i V_{a,t}^i \left(\theta_t^i, m_{t0}^i \right) \right) \quad (4)$$

We incorporate the influence of CO_2 fertilization using regional values presented in Schimel et al.[53] and empirical estimates from Davis et al.[54]. The future projections are consistent with an increase in CO2 concentration from today's level of 424 ppm to 540 in 2100 (~RCP 4.5). Under this scenario, temperate and tropical forest growth is projected to increase 7.2% per decade in the first decade, declining at 15% per decade reflecting an anticipated slowdown in atmospheric carbon accumulation. Boreal forest growth is projected to increase 3.5% in the first decade, declining at 15% per decade. All yield functions in the model reflect net yield accounting for disturbances in growth, and track changes in net biosphere productivity derived from the CMIP6 Earth Simulation Model exercise[55], as well as from Dynamic Global Vegetation Models[48].

The model does not include other potential impacts of climate change, which have the potential to substantially influence forest carbon flux dynamics and diminish the capacity of forests to store and sequester carbon[56]. Incorporating estimates of these projections is critical for comprehensive assessment of the magnitude and costs of forest-sector mitigation, particularly over time frames beyond mid-century.

The area of land in each forest type adjusts over time according to:

$$X_{a,t}^i = X_{a-1,t-1}^i - H_{a-1,t-1}^i + G_{a=0,t-1}^i + N_{a=0,t-1}^i \quad (5)$$

Initial land areas X_t^i are given, all choice variables are constrained to be greater than or equal to zero, and the area of timber harvested $H_{a,t}^i$ cannot exceed the total timber area. G_t^i is the area of land with regenerating timber and N_t^i is the area of new established forests.

The model tracks carbon in four pools: biomass carbon, soil carbon, forest product carbon, and slash. The total forest carbon pool $TFCP_t^i$ for each timber type is:

$$TFCP_t^i = \sum_a C_{a,t}^i X_{a,t}^i \quad (6)$$

Biomass carbon $C_{a,t}^i$ accounts for the carbon in the living tree, including roots, but does not include dead organic matter in slash. Carbon is proportional to total biomass, given as:

$$C_{a,t}^i = \sigma^i V_{a,t}^i \left(\theta_t^i, m_{t0}^i \right) \quad (7)$$

where σ^i is a species dependent coefficient that converts biomass to carbon and the volume is not only affected by management decisions m_{t0}^i but also by changes in forest productivity θ_t^i which are influenced by the CO_2 fertilization scenario.

Carbon in harvested forest products HC_t^i is as follows:

$$HC_t^i = \sum_a \left(\kappa^i V_{a,t}^i H_{a,t}^i \right) \quad (8)$$

where κ^i is the proportion of harvested timber that is stored permanently and is estimated to be 0.30.

Soil carbon $SOLC_t^i$ represents the stock of carbon in forest soils of type i in time t. The value of $\bar{K}$ is the steady state level of carbon in forest soils, which is unique to each region and forest type. The parameter μ^i is the growth rate for soil carbon. When land use changes, we track net carbon gains or losses from soil over time as follows:

$$SOLC_{t+1}^i = SOLC_t^i + SOLC_t^i \left(\mu^i \right) \left[\frac{\left(\bar{K} - SOLC_t^i \right)}{SOLC_t^i} \right] \quad (9)$$

Finally, we represent slash carbon AS_t^i as the carbon left over on site after a timber harvest.

$$AS_t^i = \sum_a \left(\omega_a^i V_{a,t}^i H_{a,t}^i - \kappa^i V_{a,t}^i H_{a,t}^i \right) \quad (10)$$

The stock of slash SP_t^i builds up over time, and decomposes as follows:

$$SP_{t+1}^i = AS_t^i + \left(1 - \theta^i SP_t^i \right) \quad (11)$$

Where decomposition rates θ^i differ by biome.

GTM is calibrated to regional forest inventory data, and recent analyses indicate that the model's projections of future market and land use are robust to parametric uncertainty related to forest growth and land supply parameters[51], and reflect the important role of management in the evolution of terrestrial carbon stocks historically[57].

Scenarios

We used GTM to establish a reference level of future CO_2 fluxes from forests and forest products in the absence of incentives for forest-based mitigation. This reference scenario is calibrated to macroeconomic projections of GDP and population worldwide from the Shared Socioeconomic Pathways (SSP) scenario 2 and the 2020 U.S. Annual Energy Outlook.

We represent incentives for mitigation in the form of rental payments R_t^c for carbon sequestration and annual incentives (P_t^c) for carbon stored in timber products[11,15,58]. These are included in the objective function using the term $CarbInv_t$.

$$CarbInv_t = P_t^c\left[\sum_i HC_t^i + \left(SOLC_t^i - SOLC_{t-1}^i\right)\right] + R_t^c \sum_i TFCP_t^i \quad (12)$$

The first term in this equation represents the incentives applied to Carbon transferred to long-lived wood products (HC_t^i) from each forest i valued at the carbon price P_t^c, as well as the change in soil carbon ($SOLC_t^i$) when land switches between forests and agriculture. The second term is the annual rent, $R_{t,}^c$, whereby the total carbon stocks in forests $TFCP_t^i$ are rented for the duration of time that the carbon is stored.

The rental value for carbon is:

$$R_t^c = P_t^c - P_{t+1}^c/(1+r)^t \quad (13)$$

where r is the interest rate.

In this study we simulate eight scenarios with carbon payments P_t^c starting at \$5, \$20, \$35, \$50, \$75, \$100, \$150, and \$200 and growing at 3% per year. We group these scenarios into low (<=\$20/ton CO_2) medium (\$35/ton CO_2–75/ton CO_2), and high (> \$100/ton CO_2) climate finance ranges for the purpose of visualization and reporting. Under the baseline scenario without investments in forest mitigation, $CarbInv_t = 0$.

For each scenario, the model estimates the optimal level of four potential mitigation activities in each region in response to carbon payments: avoided deforestation, forest management activities, increasing harvest rotations, and re/afforestation (including natural forest regeneration and intensively managed timber plantation establishment). There are no limits or constraints on forest-based mitigation activities at the country level outside biophysical limits already included in the model (e.g. trees could not be planted in areas that are not suitable under current climate conditions).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Code availability

GTM code used for this paper is available on the Global Timber Model Code Repository at the following link: https://u.osu.edu/forest/code-repository/. The code for this paper is included in the folder 'Austinetal2025'.

References

1. Roe, S. et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **9**, 817–828 (2019).
2. Griscom, B. W. et al. Natural climate solutions. *Proc. Natl Acad. Sci. USA* **114**, 11645–11650 (2017).
3. Grassi, G. et al. The key role of forests in meeting climate targets requires science for credible mitigation. *Nat. Clim. Change* **7**, 220–226 (2017).
4. Forsell, N. et al. Assessing the INDCs' land use, land use change, and forest emission projections. *Carbon Balance Manag.* **11**, 26 (2016).
5. Fyson, C. L. & Jeffery, M. L. Ambiguity in the land use component of mitigation contributions toward the paris agreement goals. *Earth's Future* **7**, 873–891 (2019).
6. UNFCCC. *Synthesis Report On The Aggregate Effect Of The Intended Nationally Determined Contributions. FCCC/CP/2015/7* (United Nations Framework Convention on Climate Change, Bonn, Germany, 2015).
7. Zheng, Q. et al. Future land-use competition constrains natural climate solutions. *Sci. Total Environ.* **838**, 156409 (2022).
8. Ohrel, S. B. et al. Policy perspective on the role of forest sector modeling. *J. For. Econ.* **34**, 187–204 (2019).
9. Forest Declaration Assessment, *Forest Finance: Theme 3 Assessment—Forest Declaration*. https://forestdeclaration.org/resources/forest-finance-theme-3-assessment/ (2022).
10. Intergovernmental Panel on Climate Change (IPCC), Ed., Agriculture, Forestry and Other Land Uses (AFOLU). in *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, Cambridge, (2023).
11. Austin, K. G. et al. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nat. Commun.* **11**, 5946 (2020).
12. UNFCCC, *Introduction to Climate Finance.* (United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany).
13. Zhou, K., Midkiff, D., Yin, R. & Zhang, H. Carbon finance and funding for forest sector climate solutions: a review and synthesis of the principles, policies, and practices. *Front. Environ. Sci.* **12**, 1309885 (2024).
14. Caldwell, M., Alayza, N.& Larsen, G. *Paying for the Paris Agreement.* (Report, World Resources Institute, Washington, DC, 2022).
15. Favero, A. et al. Investing in U.S. forests to mitigate climate change. *Carbon Balance Manag.* **20**, 4 (2025).
16. den Elzen, M. G. J. et al. Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitig. Adapt. Strateg. Glob. Change* **27**, 33 (2022).
17. Roe, S. et al. Bridging the gap: Sectoral transformation benchmarks, mitigation potentials and investment needs. Chapter 6 (United Nations Environment Programme, 2024).
18. UNFCCC, *Technical Dialogue of the First Global Stocktake. Synthesis Report FCCC/SB/2023/9.* https://unfccc.int/documents/631600 (UNFCCC Secretariat 2023).
19. UNFCCC, *Baku to Belém Roadmap to 1.3T: Workplan.* https://unfccc.int/documents/646798 (UNFCCC, 2025).
20. Zhu, Y. et al. China's carbon sinks from land-use change underestimated. *Nat. Clim. Chang.* **15**, 428–435 (2025).
21. Schepaschenko, D. et al. Russian forest sequesters substantially more carbon than previously reported. *Sci. Rep.* **11**, 12825 (2021).
22. Sasmito, S. D. et al. Half of land use carbon emissions in Southeast Asia can be mitigated through peat swamp forest and mangrove conservation and restoration. *Nat. Commun.* **16**, 740 (2025).
23. Republic of Indonesia, *Enhanced Nationally Determined Contributions Republic of Indonesia.* (Government of Indonesia, 2022).

24. Turner, J., Meldrum, M., Haagh, V., Ibsen, O. & Oppenheim, J. *Investments for Green Recovery and Transformational Growth 2020–30*. (The London School of Economics and Political Science, Grantham Research Institute on Climate Change and the Environment, Systemiq, 2021).
25. FOLU Coalition, *Growing Better: Ten Critical Transitions to Transform Food and Land Use*. (The Food and Land Use Coalition, 2019).
26. Deutz, A. et al. *Financing Nature: Closing the Global Biodiversity Financing Gap*. (Paulson Institute, The Nature Conservancy, Cornell Atkinson Center for Sustainability, 2020).
27. UNFCCC Standing Commitee on Finance, *Second report on the determination of the needs of developing country Parties related to implementing the Convention and the Paris Agreement*. (UNFCCC, 2024).
28. OECD, *The Climate Action Monitor 2023: Providing Information to Monitor Progress towards Net-Zero*. (OECD Publishing, Paris, 2023).
29. Piris-Cabezas, P., Lubowski, R. N. & Leslie, G. Estimating the potential of international carbon markets to increase global climate ambition. *World Dev.* **167**, 106257 (2023).
30. Edmonds, J. et al. How much could article 6 enhance nationally determined contribution ambition toward paris agreement goals through economic efficiency?. *Clim. Change Econ. (CCE)* **12**, 1–18 (2021).
31. Yu, S., Duan, M. & Edmonds, J. *Emissions Gap Report 2021: The Heat Is On. Chapter 7 The role of market mechanisms in bridging the emissions gap*. (United Nations Environment Programme, Nairobi, 2021).
32. Ward, J., Gerbode, C., Johnston, B. & Kerr, S. *Advancing Effective and Equitable Crediting: Natural Climate Solutions Crediting Handbook*. (Environmental Defense Fund, 2024).
33. Herold, A. & Böttcher, H. *Accounting of the land-use sector in nationally determined contributions (NDCs) under the Paris Agreement*. (Öko-Institut e.V. and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Bonn, Germany, 2018).
34. Sato, I., Langer, P. & Stolle, F. *NDC Enhancement: Opportunities in the Forest and Land-use Sector*. (Working Paper, World Resources Institute and United Nations Development Programme, Washington, DC and New York, NY, 2019).
35. UNFCCC, *Reference Manual for the Enhanced Transparency Framework under the Paris Agreement: Understanding the enhanced transparency framework and its linkages*. (UNFCCC, Bonn, Germany, 2022).
36. Srouji, J. et al. Next-generation Climate Targets: A 5-Point Plan for NDCs. https://www.wri.org/insights/next-ndcs-5-point-plan (2024).
37. Chu, L., Grafton, R. Q. & Nelson, H. What will it cost to achieve the COP26 Glasgow forest agreement commitment and halt global forest loss?. *World Dev. Sustainability* **3**, 100106 (2023).
38. Brown, C., Alexander, P., Arneth, A., Holman, I. & Rounsevell, M. Achievement of Paris climate goals unlikely due to time lags in the land system. *Nat. Clim. Chang.* **9**, 203–208 (2019).
39. Keppo, I. et al. Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. *Environ. Res. Lett.* **16**, 053006 (2021).
40. Luo, C., Li, S., Hua, E., Forsell, N. & Chen, M. Synthesizing mitigation ambitions and implementation of the agriculture, forestry, and other land use (AFOLU) sector. *Ecosyst. Health Sustainability* **10**, 0217 (2024).
41. Rynearson, A., Bakhtary, H. & Dyck, M. "Raising the Bar: Strengthening Forest Ambition in Nationally Determined Contribtutions (NDCs)" (WWF, Gland, Switzerland, 2024).
42. FAO, *Global Forest Resources Assessment 2020* (FAO; https://openknowledge.fao.org/handle/20.500.14283/ca9825en) (2020).
43. Tan, Z. D., Carrasco, L. R., Sutikno, S. & Taylor, D. Peatland restoration as an affordable nature-based climate solution with fire reduction and conservation co-benefits in Indonesia. *Environ. Res. Lett.* **17**, 064028 (2022).
44. United Nations Environment Programme, *Raising ambition, accelerating action Towards enhanced Nationally Determined Contributions for forests*. (2024).
45. Grassi, G. et al. Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. *Earth Syst. Sci. Data* **14**, 4643–4666 (2022).
46. Sohngen, B. & Mendelsohn, R. An Optimal Control Model of Forest Carbon Sequestration. *Am. J. Agric. Econ.* **85**, 448–457 (2003).
47. Kindermann, G. et al. Global cost estimates of reducing carbon emissions through avoided deforestation. *Proc. Natl Acad. Sci.* **105**, 10302–10307 (2008).
48. EPA, *Greenhouse Gas Mitigation Potential in the U.S. Forestry and Agriculture Sector*. (U.S. Environmental Protection Agency, Office of Atmospheric Protection, Washington, DC, 2024).
49. Kim, S. J., Baker, J. S., Sohngen, B. L. & Shell, M. Cumulative global forest carbon implications of regional bioenergy expansion policies. *Resour. Energy Econ.* **53**, 198–219 (2018).
50. Tian, X. et al. Forests continue to be a carbon sink? *Land Econ.* **94**, 97–113 (2018).
51. Sohngen, B., Salem, M. E., Baker, J. S., Shell, M. J. & Kim, S. J. The Influence of Parametric Uncertainty on Projections of Forest Land Use, Carbon, and Markets. *J. Econ.* **34**, 129–158 (2019).
52. Daigneault, A. & Favero, A. Global forest management, carbon sequestration and bioenergy supply under alternative shared socioeconomic pathways. *Land Use Policy* **103**, 105302 (2021).
53. Schimel, D., Stephens, B. B. & Fisher, J. B. Effect of increasing CO_2 on the terrestrial carbon cycle. *Proc. Natl Acad. Sci.* **112**, 436–441 (2015).
54. Davis, E. C., Sohngen, B. & Lewis, D. J. The effect of carbon fertilization on naturally regenerated and planted US forests. *Nat. Commun.* **13**, 5490 (2022).
55. Canadell, J. et al. *Global carbon and other biogeochemical cycles and feedbacks*. (Intergovernmental Panel on Climate Change (IPCC)., Cambridge, UK and New York, NY, USA, 2023).
56. Bousfield, C. G., Lindenmayer, D. B. & Edwards, D. P. Substantial and increasing global losses of timber-producing forest due to wildfires. *Nat. Geosci.* **16**, 1145–1150 (2023).
57. Mendelsohn, R. & Sohngen, B. The net carbon emissions from historic land use and land use change. *J. For. Econ.* **34**, 263–283 (2019).
58. Favero, A., Daigneault, A. & Sohngen, B. Forests: carbon sequestration, biomass energy, or both? *Sci. Adv.* **6**, eaay6792 (2020).
59. R Core Team, *R: A language and environment for statistical computing, version 4.4.3, R foundation for statistical computing*. https://www.R-project.org/ (2025).
60. Garnier, S. et al. *viridis(Lite) - Colorblind-friendly color maps for R, version 0.6.5;* https://sjmgarnier.github.io/viridis/ (2024).
61. P. Massicotte, A. *South, rnaturalearth: World Map Data from Natural Earth, version 1.0.1* https://CRAN.R-project.org/package=rnaturalearth (2023).
62. Wickham, H. *Ggplot2: Elegant Graphics for Data Analysis* (Springer-Verlag New York, 2016).

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