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RESEARCH

Investing in U.S. forests to mitigate climate change

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Abstract

In recent years several U.S. federal policies have been adopted to support forest-based climate mitigation actions. This study focuses on current federal funds allocated to forest for climate change mitigation activities to assess how much they could deliver in terms of net sequestration under a best-case (optimized) scenario where the cheapest abatement options are implemented first and if these funds are in line to achieve domestic targets for 2030 and 2050. Multiple investments pathways are tested under two different assumptions on CO_2 fertilization to provide a range of future mitigation projections from forests. Results show that under annual investments in line with current federal funds (around \$640 million), the expected net carbon flux of U.S. forests is around 745 $MtCO_2$/yr in 2030 (+ 12% increase from baseline) and if the investments expand after 2030 the net flux is expected to be 786 $MtCO_2$/yr in 2050 (+ 17% increase from baseline). When CO_2 fertilization is accounted for, the projections of net forest carbon sequestration increase by 17% in 2030 and about 1 $GtCO_2$ net sequestration achieved under federal funds in 2050, increasing the likelihood of meeting both short-term and long-term domestic targets.

Introduction

Forests have been acknowledged as playing an increasingly important role in U.S. actions to mitigate national GHG emissions and improve carbon sequestration capacity. Under the Nationally Determined Contribution (NDC), the U.S. has set a goal to reduce net GHG emissions by 61–66% compared to 2005 levels in 2035 and the forestry sector is expected to play an important role.[1] Under the 2021 U.S. Long Term Strategy (LTS) about 1 $GtCO_2e\ yr^{-1}$ of net CO_2e sequestration is projected from land-based activities to achieve the U.S. 2050 net-zero emissions target.[2] Recent studies show that the forest sector could remain a natural net carbon sink without policies specifically investing in abatement activities such as reforestation and improved forest management, but the sequestration rate could potentially decline without targeted investments and policy levers designed to improve carbon sequestration outcomes [13, 22, 27, 38].

In light of these needs, in recent years, several U.S. federal policies have been adopted with specific goals or budget allocations to support forest-based climate mitigation actions (see Table S1). The 2022 Inflation Reduction Act (IRA),[3] one of the most significant pieces of U.S. climate legislation to date, directed a total around \$7 billion investments in the next nine years in the forestry sector with about 70% dedicated to investments in climate smart forestry and conservation activities. The 2021 Bipartisan Infrastructure Investment and Jobs Act (IIJA)[4]

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[1] United States NDC, December 2024: https://unfccc.int/sites/default/files/2024-12/United%20States%202035%20NDC.pdf.

[2] The Long-Term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050 (whitehouse.gov).

[3] https://www.usda.gov/ira.

[4] Investing in our future|US Forest Service (usda.gov).

provides about \$7 billion to the forest sector until 2030, mainly for tackling pressing issues including to increase wildfire fuel removal and 13% of the funds are allocated to develop national reforestation plans and encourage innovation in the wood products industry. Other federal initiatives such as the REPLANT Act[5] and the Partnership for Climate Smart Commodities[6] could also support forest-based mitigation investments in the U.S.

This study has three objectives. First, it estimates future CO_2 fluxes from forest ecosystem pools in forests and harvested wood under different levels of investment in forest mitigation activities in the U.S. Second, it explores the expected flux that could be delivered under the funds allocated under the IRA and IIJA for forest-based mitigation activities. The study presents this as the best-case scenario where all U.S. forests are eligible to participate to these programs—even if current eligibility varies across programs—and the cheapest mitigation options are implemented first. The cost-effective mix of forest-based mitigation activities is compared to the current allocation of federal funds to assess their divergence. Furthermore, it estimates how well current federal fund could achieve relative to the expected mitigation from forests under the 2030 and 2050 domestic goals. Finally, it assesses how these outcomes are affected by a different parameter on forest productivity, both through investment and natural processes.

Currently, there are few published articles that explicitly assess the potential impacts of recently allocated federal funds on forest-based mitigation activities in the United States. Favero et al. [19] used the dynamic model FASOMGHG to estimate land-mitigation pathways under different level of investments (directed to both agriculture and forests) in the short term and reported that the U.S. forests will deliver about 50.4 $MtCO_2$/yr under land-mitigation investments of 2.4 billion in 2030. Coulston et al. [7] used a detailed simulation framework to quantify the potential emissions implications of funding allocation targeting fuel removal and afforestation and found that these investments could reduce the carbon sink of U.S. forests near term. However, this analysis used exogenously defined scenarios and did not consider the impact of different investment levels or carbon payments on forest management or the feedback loop between forest management, land use, carbon sequestration, and markets. In another recent paper, Bistline et al. [3] estimated the effects of IRA funds on key U.S. sectors including the land sector (both forestry and agriculture) projecting a maximum of 92 $MtCO_2e$/yr net sequestration, but this analysis does not include a detailed representation of the U.S. or global forestry sector.

[5] REPLANT Factsheet.pdf (senate.gov).

[6] Partnerships for Climate-Smart Commodities|USDA.

Methods

This study uses an open source intertemporal economic optimization model of the global forest sector (Global Timber Model, GTM) to answer these questions (see the Supporting Information for a detailed description of the model). GTM is used to establish a reference level of future CO_2 fluxes from forests (and forest products) in the absence of investments targeting forest-based climate mitigation activities. In GTM mitigation incentives are represented in the form of rental payments for carbon sequestration and annual subsidies for carbon in timber products [13]. The scenario design applied in this analysis includes 12 pathways with varying carbon payments for forest-based mitigation activities starting between \$5 and \$100/tCO_2e and rising over time at two different rates. We group these scenarios into seven groups: (1) No investments; (2) IRA + IIJA (investments = \$640 million per year between now and 2030); (3) IRA + IIJA continued after 2030 (investments of \$640 million per continue after 2030); (4) Investments in forest mitigation above the IRA + IIJA and below \$2.5 billion per year between now and 2050; (5) Investments in forest mitigation above \$2.5 and below \$4.5 billion per year between now and 2050; (6) Investments in forest mitigation above \$4.5 and below \$8.0 billion per year between now and 2050; (7) "High Ambition" scenario which included all the runs that are projecting investments higher than \$8.0 billion/yr and are consistent with carbon incentives higher than \$40/tCO_2 in 2030. Model investments are calculated *ex-post* by discounting annual expenditures to compensate landowners for their forest-based mitigation activities.

These investment scenarios are replicated under two alternative assumptions on the effect of carbon fertilization on forest growth: (i) no fertilization and (ii) full carbon fertilization under atmospheric CO_2 accumulation consistent with the Representative Concentration Pathway (RCP) 4.5. Finally, both scenarios include disturbances to global forests that are not managed.

Instead of examining investments proposed for specific activities in the forestry sector, this paper implements a dynamic economic modeling to project the cost-effective mix of activities under alternative levels of investments and compare them to a scenario without investments (baseline), extending similar analyses presented in Austin et al. [2]. Both federal policies included in this study have a relatively short implementation time frame (between now and 2030). Given that forest-based actions require time to deliver the expected abatement outcome, the results focus on both the 2030 shorter and the 2050 longer time frame.

GTM was chosen for this research because of its ability to optimize forest-based carbon sequestration investments across space and time, while connecting U.S. forestry to global forest markets, making it particularly suited for assessing the long-term implications of policy-driven financial incentives. Moreover, GTM is specifically designed to capture the complexities of forest management decisions under different investment incentive scenarios. Specifically, under different carbon prices, GTM scenarios offer insight into the potential cost-effectiveness (and market opportunity costs) of a range of forest-based mitigation strategies, including avoided deforestation, reforestation, improved forest management, and changes in harvest rotations, all of which are essential to understanding how federal funding can influence U.S. forest carbon sequestration [9]. Furthermore, we exploit GTM's ability to incorporate different climate variables impacting forest productivity, such as varying levels of CO_2 fertilization, enhances the robustness of our findings by accounting for uncertainties in forest growth responses to rising atmospheric CO_2 levels [12]. This approach provides a more nuanced understanding of the complex interactions between forest productivity and climate, which is crucial for optimizing federal investments to meet U.S. carbon mitigation goals for 2030 and 2050. By offering a detailed and flexible framework, GTM delivers valuable insights for policymakers in designing future climate strategies, particularly in balancing cost and effectiveness over time [15, 16].

Results

No investments (baseline)

Under a scenario without direct investments, forests in the U.S. remain a net carbon sink through 2050, including fluxes from natural and managed forests, with a projected annual net sequestration of 622 $MtCO_2$ in 2025 and 650 $MtCO_2$ in 2050 (Fig. 1A, *black line*). This trend is driven by increasing global demand for forest-based products under the baseline scenario, with population and economic growth aligned to the Shared Socioeconomic Pathway scenario SSP2 (middle of the road). Forest management interventions and investment counterbalance slowing sequestration rates from aging unmanaged forests. The increase in demandboosts prices in the baseline driving investment in marginal land in the U.S. to be converted into forests, as well as additional investments in productivity-enhancing forest management relative to present level (which could include advanced silviculture, changing rotational strategies, using genetically improved seedlings, and increasing stocking density, among other strategies). These baseline land and forest management investments, driven by market changes, increase the stock of carbon in forests and harvested wood products, which are similar to the results of Daigneault et al. [9] and Tian et al. (2018).

Investment pathways

Annual forest net fluxes are estimated under different investment levels between 2025 and 2050 (Fig. 1A). The first wedge (IRA + IIJA) shows the expected net sequestration from forest and timber products under annual investments of $640 million which are in line with the estimated funds available for forest-based mitigation strategies under the IRA and IIJA together. In 2030, these investments drive an increase in net forest sequestration of 88 $MtCO_{2.}$ After 2030, we simulate two scenarios: one scenario in which investments stop resulting in net forest sequestration stabilizing at around 740 $MtCO_2$ (dark orange wedge) and one scenario in which IRA + IIJA funds are extended with a projected net flux of 786 $MtCO_2$ in 2050 (136 $MtCO_2$ mitigation).

By testing other investment scenarios, results show that under annual investments between now and 2050 of around $ 2.5 billion, the net flux of carbon in forests could reach 995 $MtCO_2$, around 52% more carbon sequestration than the baseline in 2050. As the level of investment increases, more sequestration is projected, but this growth is not proportional to the dollar invested. For instance, under annual investments of $8 billion, the net flux increases by 27% reaching 1,263 $MtCO_2$/yr in 2050 and showing declining marginal returns. Finally, the "high ambition" wedge represents the maximum additional sequestration projected under the simulated scenarios for investments higher than $8 billion per year.

The implicit carbon price consistent with current federal funds is around 21 $/tCO_2$ in 2030. It is useful to compare this value to the implicit price used in other mitigation activities outside forestry (e.g. energy sector) under federal investments scenarios. For instance, Bistline et al. [3] assumes an average implicit carbon equivalent prices of $27–102/$tCO_2$e across sectors in 2030. This comparison shows the potential for low-cost mitigation opportunities in the forestry sector relative to the other sectors included in their analysis.

Mitigation activities

GTM responds to forest investments by selecting the cost-effective mix of mitigation activities available, which requires weighing both current and future returns on investments, the costs of planting new forests (including the avoided rent from the current uses of land), land management costs, current and future timber demand and revenues, all subject to resource constraints and biophysical characteristics of forests (e.g. forest age class

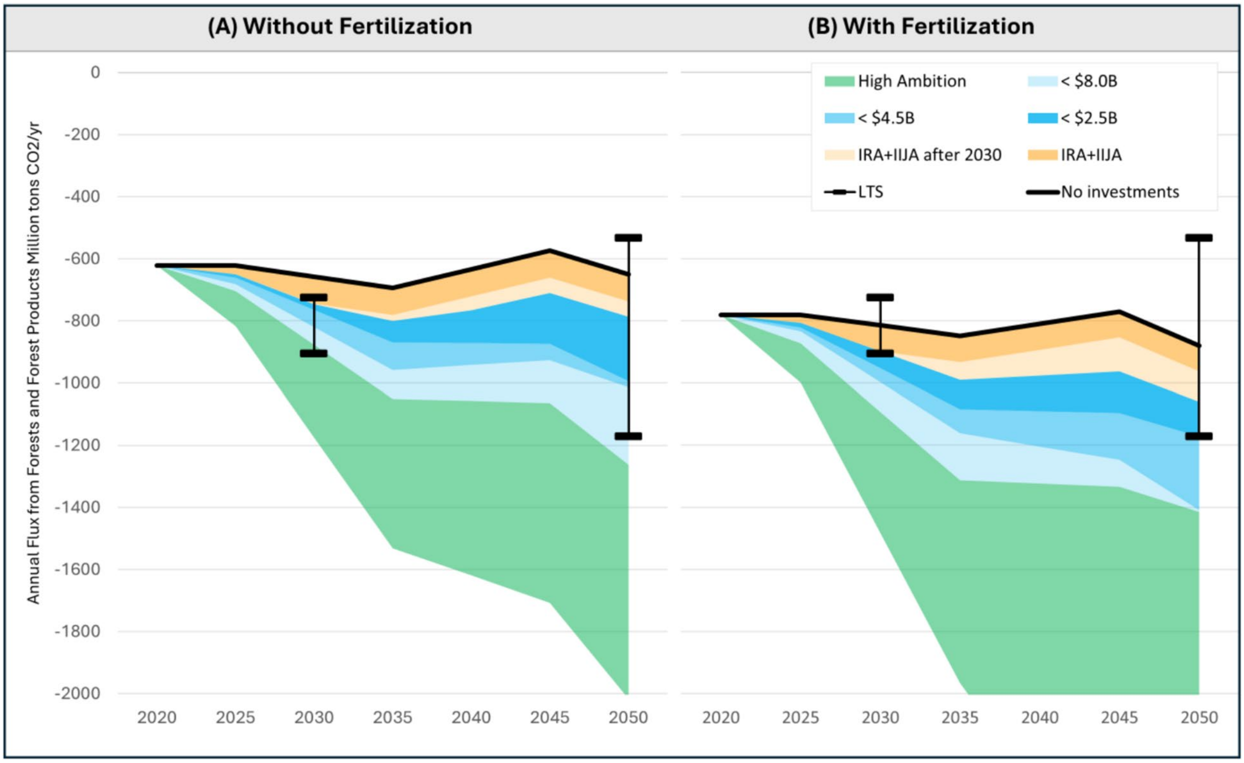

Fig. 1 Projected Annual Net CO_2 Flux from Forest Ecosystem Pools in Forests and Harvested Wood (Million Tons CO_2) under different levels of investments without and with CO_2 fertilization. The figure shows the annual net CO_2 flux from forest ecosystem pools in forests and harvested wood across different levels of annual discounted investments from GTM from 2025 to 2050 without and with CO_2 fertilization. Results are presented in terms of atmospheric accounting. Therefore, positive net flux equates emissions; negative net flux represents sequestration. Fluxes are aggregated by level of investments: the black lines show the flux in the baseline scenario (without investments), the dark orange wedge shows projected emissions under the IRA + IIJA investments applied from now to 2030, the light orange shows fluxes under the case IRA + IIJA investments then extended after 2030. The blue wedges show fluxes under annual investments greater than $640 million (IRA + IIJA) and lower than $2.5 billion; greater than $2.5 billion and lower than $4.5 billion and greater than $4.5 billion and lower than $8 billion. The green wedge shows fluxes under annual investments greater than $8 billion up to 2 $GtCO_2$ in 2050 (High Ambition). The black bars show the range of net CO_2 flux under the Long Term Strategy (LTS) in 2030 and 2050 estimated using the data from Figure 18 of the U.S. Department of State & the U.S. Executive Office of the President. 2021. "The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050" and assuming that the proportion of LULUCF net sink from forests remains equal to 85% in the future as in 2019

structure). The mix of potential abatement activities in response to programmatic investments in forest carbon includes (i) changing forest management intensity to improve productivity, (ii) extending forest rotations, (iii) converting land into forests (reforestation and/or afforestation), (iv) changing harvest levels both time and location, and (v) altering the wood product mix to store carbon in long-lived wood product pools. GTM includes also emissions reductions from avoided deforestation but that element does not apply to the U.S.

Under all investment scenarios forest area is expected to increase with an average increase of 0.8 Million hectare (Mha) per year by 2050 under the IRA + IIJA scenario and a rate of 2.3 Mha/yr under High Ambition scenario and half of that increase is projected in the South and 40% in the Northeast and Midwest.

Under the IRA + IIJA scenario, in 2030 around 28% of mitigation is expected from changes in forest management while the rest is coming from reforestation activities and less than 5% from additional carbon stored in timber products. In reality, the estimated allocation of current federal funds is distributed to forest management activities (52%), reforestation activities (38%) (e.g. Section 21002 (a) (2) which support tree planting) and wood innovation and carbon stored in wood products (10%). Despite the current allocation of funds does not exactly align with the projected optimal mix of activities from GTM, the allocation and model-produced mixes both show a diversify portfolio of activities instead of focusing on only one activity, emphasizing synergies across the relative outcomes. Moreover, this difference potentially highlights ways in which future funding could consider the allocation of resources.

GTM also disaggregated forest carbon pools into four categories which allows to explore how price incentives will drive changes in each of them. Under the IRA + IIJA scenario, the largest share of mitigation (> 80%) comes from additional above ground carbon relative to the scenario without investments from both changes in management (more carbon sequestered per current forest area) and conversion of land to forests which also increases carbon stored in soil (> 5% average mitigation). Finally, a small portion of mitigation (< 5%) comes from more carbon stored in long-lived timber products.

Domestic targets

The net carbon fluxes from the forest ecosystem under the IRA and JIIA funding programs are compared with the estimated range[7] of Land Use, Land Use Change and Forestry (LULUCF) net fluxes projected under the Long Term Strategy (LTS) to assess both the feasibility of the mitigation target and the need for additional activities (public and private) to enhance the forests' mitigation potential. Results here indicate that by 2030, the current allocation of IRA + IIJA funds fall toward with the upper end of the LULUCF projection range (723–904 $MtCO_2$/yr), though additional investments are necessary to cover the full range (i.e., the highest mitigation volumes achieved in GTM). This outcome suggests that while the target is achievable, non-federal investments will likely be crucial for reaching it. By 2050, the LTS projection range expands to 532–1170 $MtCO_2$/yr, and the expected mitigation from federal funds falls within this range (Fig. 1, black bars). This underscores the importance of both private sector investments and market mechanisms outside of federal interventions in meeting long-term mitigation goals.

International timber market

In this analysis, the price incentives driving forest carbon mitigation in U.S. forests are also applied globally. This approach allows for evaluation how market dynamics are influenced by investments and assess the impact on timber markets at both the U.S. and global levels at different investment levels, without leakage. Global results indicate that average harvesting levels are projected to shift between − 21% and + 29% from 2025 to 2050 under carbon mitigation investments in forests and timber products. For the U.S., harvesting changes are expected to range from − 5% to + 2% relative to the no-investment scenario by 2050. Additionally, the composition of timber production is expected to shift, with a higher proportion of sawtimber relative to pulpwood being produced in the U.S., leading to an increase in carbon stored in wood products.

The introduction of global incentives for forest carbon mitigation is also altering the regional supply of timber, with some countries gaining global market share while others see a decline. The U.S. is projected to maintain its share of global timber supply at around 17%. This outcome results from changes in domestic harvesting decisions aimed at preserving forest carbon stocks, as well as shifts in forest management practices in other countries.

CO_2 fertilization

This analysis also highlights the positive impacts of CO_2 fertilization on forests' natural productivity, which results in increased carbon sequestration for all scenarios (Fig. 1B). Under the baseline case, fertilized forests in the U.S. are projected to increase the sequestration rate by 24% in 2030 and 35% in 2050 relative to no fertilization case. In 2050, forests are expected to sequester around 880 $MtCO_2$ without directed investments in mitigation activities. CO_2 fertilization is particularly important for young forests, and thus has a really strong effect in the southern U.S. with its large area of plantations.

Including the annual investments of the IRA and IIJA, the expected net CO_2 flux of forests is 17% higher in 2030, and 26% in 2050 relative to the no fertilization scenario. The effects of fertilization are particularly significant in the long run. In 2050 the increase in natural productivity drives more forest sequestration per dollar invested. For instance, under the IRA + IIJA scenario, investing $640 million per year could deliver as much sequestration as investing more than $2.5 per year without CO_2 fertilization between 2025–2050.

Discussion

This paper provides one of the first estimates of future net carbon fluxes from the U.S. forests under different investments pathways, with and without climate change-induced shifts in CO_2 fertilization, by using the economic model GTM. The results presented in this study could be used to inform policymakers on the level of mitigation achieved by forest under the current funds and assess its potential under different level of investments with and without changes in natural forest productivity. We show that a $640 million per year investment from the IRA and IIJA will result in a 12% increase from baseline flux with a mitigation of 88 $MtCO_2$ and if the investments extend after 2030 the flux is expected to be 28% more than the baseline in 2050.

[7] Both domestic targets are estimated using the data from Figure 18 of the U.S. Department of State & the U.S. Executive Office of the President. 2021. "The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050" assuming that the proportion of LULUCF net sink from Forest Ecosystem Pools in Forests and Harvested Wood Pools in 2019 remains equal to 85% in the future.

Similar results have found in Favero et al. [19]. The study utilizes a different dynamic model, FASOMGHG, to assess the mitigation potential of the entire U.S. land sector under more generic investments pathways. Authors estimate that under $2.4 billion in investments by 2030, forests could deliver approximately 51 $MtCO_2$ in mitigation, while agriculture could contribute 29 $MtCO_2$. Each model has its strengths and limitations, and the findings from this study can be integrated with other results to enhance our understanding of forests' future role in mitigating climate change. While models like FASOMGHG are strong at integrating agricultural, forestry, and bioenergy sectors at the domestic level, they often lack the necessary granularity to model forestry-specific investment pathways in detail or to fully capture global market dynamics.

On the other hand, Coulston et al. [7] focus only on the IIJA and estimate that it would result in a net decrease in forest carbon between 2019 and 2032, as removals associated with fuel treatments would be greater than carbon gains from reforestation projects. However, they do find that net carbon sequestration could increase between 2032 and 2050, once forests have more time to respond to the treatments implemented. A key difference between Coulston et al. [7] and our analysis is how each model accounts for forest management. GTM simulates management through additional investments in carbon stock while , Coulston et al. [7], accounts for management such as thinning through explicit removal of biomass/carbon, which causes an initial decline in standing carbon stocks that the residual biomass to grow at a faster rate due to reduced competition. Both models account for carbon in harvested wood products, where small diameter biomass is treated as an immediate emission.

As our study focuses only on the IRA and IIJA, it is important to note that these programs are relatively new programs intended to incentivize forest management for improved carbon sequestration. However, private forest landowners have been incentivized to maintain and enhance a range of ecosystem services through other national and state sponsored incentives for decades. For example, landowners have received property, income, and corporate tax breaks for planting trees and actively managing their forests [14] (Kilgore et al. 2017) for the purpose of incentivizing greater management expenditures that result in higher forest productivity, GHG mitigation, and improved water quality [5, 23]. Daigneault et al. [10] estimate that U.S. forests sequester about 60 $MtCO_2$/yr of additional carbon every year because of the current tax provisions, equivalent to facing a carbon price of \$70/tCO_2 in the no tax policy baseline.

Moreover, while forestry-based investments from the IRA and IIJA will be distributed by several agencies, the funds allocated for forest management will be a substantial increase from the status quo and provide a constant monetary flow. For instance, total U.S. forest sector capital investment (e.g., equipment, forest infrastructure, land acquisition) and annual expenditure (e.g., rent, taxes, administration) in 2020 was $242 billion, with private entities making up 97% of the total estimate [25]. In 2020, the USDA Forest Service allocated $535 million in capital investment towards managing and protecting forests—largely through facilities, roads, and land acquisition, a 60% increase from 2006 [25]. However, in 2021, the USFS only invested $143 million in capital improvements, highlighting that federal investment in forests can fluctuate substantially on a year-to-year basis [37].

Finally, our study is not without limitations that could be improved in future research.

First, GTM only accounts for the forest sector and does not capture carbon fluxes resulting from interactions with the agricultural sector. If investments in cropland also change as a result of these federal policies, our estimated carbon impacts may differ (see the additional sensitivity analysis in Supplementary Information).

Second, we model investment by translating the annual budget for forest-based mitigation activities from the IRA and IIJA into a carbon price, which is then used to incentivize the cost-optimal mix of forest-related activities that achieve the maximum possible carbon sequestration under a specific incentive. In reality, these policies target specific practices that will be organized and incentivized through various government agencies and programs, which often rely on inefficient policy instruments. As a result, we may overestimate the potential carbon reductions and/or their timing.

Third, we do not model changes in the demand for timber products from the energy or construction sectors, as explored in studies by Favero et al. (2020) [15, 16]. This scenario design was chosen to focus the assessment on direct mitigation from forests, without considering future land demand and changes in land management driven by decarbonization activities in other sectors.

Finally, GTM does not examine the full range of climate change effects on forest mitigation, as the version used in this study accounts only for existing disturbances. Other studies have tested GTM scenarios involving CO2 fertilization to enhance forest growth [12, 32] and climate change impacts on forests [17, 18, 36]. Therefore, future research could combine investments in mitigation with adaptation strategies under a changing climate.

Supplementary Information

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Supplementary Material 1.

Author contributions
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Availability of data and materials
No datasets were generated or analysed during the current study.

Code availability
GTM code used for this paper is available on Global Timber Model Code Repository|Global Forests (osu.edu).

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Disclaimer
The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.

Competing interests
The authors declare no competing interests.

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