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Forest carbon tax and reward: regulating greenhouse gas emissions from industrial logging and deforestation in the US

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Abstract

Industrial logging activities associated with land development, agricultural expansion, and tree plantations generate significant greenhouse gas emissions and may undermine climate resilience by making the land more vulnerable to heat waves, water shortages, wildfires, flooding, and other stressors. This paper investigates whether a market-based mechanism—a forest carbon tax and reward program—could play a role in mitigating these climate impacts while advancing the Glasgow Leaders Declaration on Forests and Land Use, which seeks to end deforestation and forest degradation by 2030. We do this by describing key differences between the natural and industrial forest carbon cycle, identifying design features of a program that mimics existing carbon tax mechanisms, demonstrating how that program could be implemented using four US states as an example and completing a cash flow analysis to gauge potential effects on forestland investors. Across the states, we estimate the range of taxable GHG emissions to be 22–57 Mt CO_2-e yr^{-1}, emissions factors of 0.91–2.31 Mg C m^{-3}, and potential tax revenues of \$56 to \$357 million USD yr^{-1}. A model of net present value and internal rate of return for a representative forestland investor suggests that while the tax may reduce profitability somewhat (~ 30%) for a 100,000-acre (40,486 ha) acquisition, it would still generate an attractive rate of return (> 7%), especially for patient capital investors. We conclude that a forest carbon tax program is feasible with existing data available to US state agencies and could be a significant source of funding to promote climate smart forest practices without major disruptions of timber supply or forestland investments.

Keywords Carbon tax · Deforestation · Greenhouse gas emissions · Climate smart forestry · Carbon accounting

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1 Introduction

In their latest state of the climate report, Ripple et al. (2023) warn that the world is entering uncharted territory as evidenced by new all-time climate-related records and deeply concerning patterns of climate-related disasters. Deforestation and forest degradation are a major driver of climate change, accounting for at least twenty-five percent of global greenhouse gas (GHG) emissions (Pearson et al., 2017) while amplifying climate risks to vulnerable populations from heat waves (Lejeune et al., 2018), flooding (Johnson & Alila, 2023) and other climate stressors. This reality is a key motivation for The Glasgow Leaders Declaration on Forests and Land Use, which calls for an end to deforestation and land degradation by 2030. Market-based mechanisms can play an important role in meeting this global ambition.

To date, the focus of research and experimentation on market-based interventions to halt and reverse deforestation and forest degradation has been on developing and improving markets for carbon offsets, which allow entities facing high costs of reducing GHG emissions to meet their compliance or voluntary obligations by investing in lower cost forestry projects that reduce GHG emissions from that sector instead (van Kooten & Johnston, 2016). The United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD+) program is a major source of such offsets and one designed to generate a host of co-benefits for sustainable development (Milbank et al., 2018). However, REDD+ and other forest carbon offsets have been under intense scrutiny for failing to deliver real, additional, and permanent emissions reductions or slow deforestation (Haya et al., 2023; West et al., 2023). Another market-based approach is being tested by New Zealand, which has folded some deforestation-related GHG emissions into its emissions trading scheme. Under that program, forestland owners are liable for deforestation-related emissions from permanently clearing forestlands but also recipients of payments for carbon sequestration and storage (Carver et al., 2022). The program does not, however, address GHG emissions from industrial logging activities that do not involve forestland conversion. Other market-based approaches in existence include various kinds of subsidies to forestland owners, such as payments for ecosystem services (PES) that include a forest carbon component. A key drawback of subsidy-only approaches, however, is that they are funded by general tax collections and as such in violation of the international polluter pays principle (Farber, 2004). Entities responsible for GHG pollution from deforestation and forest degradation face no cost for this pollution.

Carbon taxes on GHG emissions from logging activities offer another market-based approach that has thus far received little attention. The World Bank has noted a global deficiency in use of environmental (Pigouvian) taxes despite recent evidence finding a negative and statistically significant relationship between such taxes and CO_2 emissions (Wolde-Rufael & Mulat, 2023). They are also a direct application of the polluter pays principle and are the theoretically preferred remedy among many economists for the problem of harmful externalities (Shavell, 2011). Thus far, research on the use of carbon taxes to slow and reverse deforestation and forest degradation has been limited to scenarios where carbon taxes on fossil fuels are used to finance beneficial forestry projects that reduce wildfire risk, enhance sequestration, or protect and restore tropical forests (Barbier et al., 2020; Caurla et al., 2013; Pacheco, 2021). One notable exception is Liu and Wu (2017), who considered a tax based on the carbon content of wood harvested coupled with a subsidy (reward) for sequestration—the approach embodied in this paper. The overall aim of this study is to develop this idea a step further by demonstrating how such an approach can be operationalized using four US states (Oregon, Washington, Maine and North Carolina) as examples.

As modeled in this paper, a state-level forest carbon tax and reward program would require jurisdictions to track GHG emissions from industrial logging activities, derive emissions factors for any given volume and type of harvest, apply a tax based on the social cost of carbon, and develop a system of exemptions and credits to accelerate uptake of climate smart practices such as long harvest rotations, alternatives to clearcutting, and forest carbon reserves that minimize forestland loss and help restore degraded lands to their natural state of climate regulation. It would also capitalize a forest carbon incentive fund to sustain ongoing investments in protecting and restoring carbon rich forests.

The idea of tracking and regulating GHG emissions from industrial logging activities is not without controversy. Many argue that wood products for either bioenergy or building materials are carbon neutral with respect to biogenic carbon since whatever is released is eventually recaptured by new growth and that wood products are less energy intensive than many substitutes and should be promoted as a matter of climate policy (Hoxha et al., 2020; Skog, 2014). As such, GHG emissions from logging need not be tabulated or regulated. Another common claim is that intensively managed forestlands are better at carbon sequestration than older forests, and thus, the conversion of natural forests to plantations is not a major concern with respect to forest carbon management (Ameray et al., 2021). Other research concludes the opposite—that failure to account for emissions from logging activities represents a major gap in GHG inventories (Hudiburg et al., 2019; Pearson et al., 2017), that dense forest carbon stocks of mature and old growth forests will never be replaced by plantations (DellaSala et al., 2022; Law et al., 2018) and that wood substitution benefits are substantially exaggerated (Harmon, 2019; Peng et al., 2023). And as discussed in Sect. 2, evidence suggests that the "catch and release" carbon cycle associated with intensively logged plantation landscapes results in a net increase in GHG emissions relative to the "catch and store" carbon cycle inherent to the natural forests they have replaced and thus works to maintain GHG concentrations in the atmosphere and radiative forcing well above the pre-industrial (1750) baseline.

Having in place consistent programs to account for logging-related GHG emissions, as proposed and demonstrated here, will generate critical information to help resolve these conflicting conclusions while at the same time laying the groundwork for a forest carbon tax option to bolster carbon storage and sequestration on the landscape—a widely embraced goal irrespective of divergent perspectives on the climate impacts of industrial logging activities.

A roadmap to the remainder of this publication is as follows. In Sect. 2, we provide a brief review of differences between the natural and industrial forest carbon cycle to identify GHG emission sources and adverse climate impacts that could be addressed by a forest carbon tax and reward program. We also provide an overview of climate smart alternatives to industrial practices that can reduce emissions and improve climate resiliency while maintaining adequate timber supplies. In Sect. 3, we discuss key program design features that would need to be addressed by any state-level rulemaking process. In Sect. 4, we present methods and data sources used in our four-state model of taxable GHG emissions from logging activities as well as a cash flow model used to assess potential impacts on a representative forestland investor under three policy scenarios with and without the tax. Results and comparisons to prior research are presented and discussed in Sect. 5. Conclusions and future research are discussed in Sect. 6. Broadly, we conclude that a forest carbon tax and reward program is feasible given the current state of knowledge and capabilities of state-level agencies in the US and that such programs have the potential to incentivize and generate substantial funding for climate smart forest practices without major disruptions of timber supply or forestland investments.

2 Forest carbon dynamics in natural vs. industrial landscapes

One of the most important sources of deforestation and forest degradation is the conversion of natural forestlands to tree plantations to sustain the world's growing appetite for wood and paper products. In the most productive zones—such as the Pacific Northwest coastal region or the Southeastern US—most of the forested land base has been cut over at least once and in many cases three or four times with all but a fraction of the big, old, carbon rich native trees remaining (Barton & Keeton, 2018; Gray et al., 2009). The most intensively managed lands today are logged every 25 or 30 years, planted with genetically improved monocultures, sprayed with chemical pesticides and herbicides, fertilized, and burned to clear the way for another crop. Puettmann et al. (2015) estimate that about 30% of global forestlands are managed with one form or another of these intensive, commodity production practices. As with intensive agriculture, these activities represent a major disruption of the natural carbon cycle that is generating substantial upward pressure on atmospheric concentrations of CO_2 and other greenhouse gases.

Figure 1 illustrates key differences. The natural forest carbon cycle is depicted in Fig. 1a as nature's baseline. Through photosynthesis, natural forests sequester carbon dioxide, convert it to carbon, and store it both above ground in trees and other vegetation and below ground in root systems and networks of mycorrhizal fungi that are key for sustaining long term site productivity (Fellbaum et al., 2012; Frey, 2019). For a given forested landscape, the rate of carbon sequestration, as measured by net ecosystem productivity (NEP), depends on the distribution of seral stages at any one time, but the amount of carbon stored increases in accordance with a typical Monod (cumulative increase at a decreasing rate)

(a) Nature's baseline (catch and store)

(b) Industrial tree farming (catch and release)

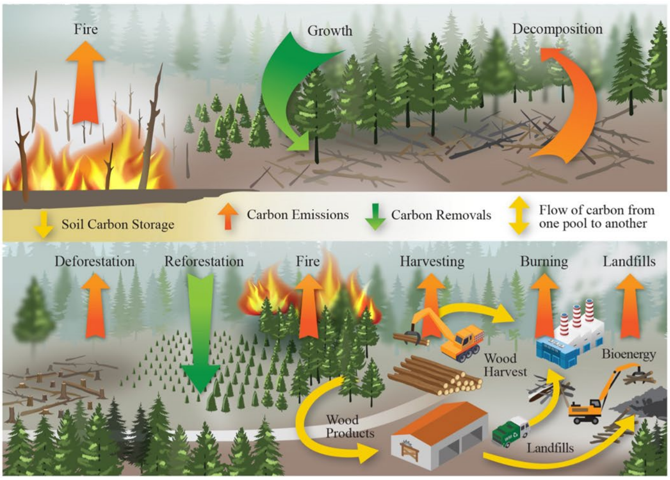

Fig. 1 Compared with natural forest conditions, industrial tree farming emits more carbon, stores less, and sequesters less on an annual basis. The two regimes can be thought of as carbon catch and store vs. catch and release

function for centuries. In general, the older the stand, the higher its carbon stocks (DellaSala et al., 2022; Gray et al., 2016; Stephenson et al., 2014).

When trees die through advanced age, insects, disease, wildfire or other disturbances and fall to the forest floor most of their carbon stocks slowly decay into the soil and are stored there in organic form. The rest is emitted into the atmosphere. The key insight is the relative magnitude of these flows. Natural forest landscapes take in significantly more carbon than they release through decay, wildfire, and other disturbances and thereby build up soil carbon over millennium, where it stays safely locked away (Hudiburg et al., 2019; Luyssaert et al., 2008). For example, Paciorek et al. (2022) found upper Midwest forestlands gained almost a billion tons of carbon over 8000 years, doubling their carbon storage. Undisturbed, the natural forest carbon cycle can thus be thought of as a “catch and store” regime.

In contrast, the industrial forest carbon cycle, depicted in Fig. 1b is one that stores and sequesters less carbon and emits more through many more channels (Liao et al., 2010). When natural forests are deforested through clearcutting and replaced with logging roads and young timber plantations, the large pool of carbon stored in big trees, snags, and downed logs is eventually emitted as CO_2 into the atmosphere. In that same Midwestern study, Paciorek et al. (2022) found that in the span of just 150 years, almost all the carbon stock 8000+ years in the making was vented into the atmosphere as a result of logging and land use conversion. This carbon storage deficit is reflected in the difference between carbon stored in remnant old growth forests versus what is stored in industrial landscapes (Fig. 2a).

In addition to releasing stored carbon, intensive logging practices diminish the natural level of carbon sequestration across the landscape (Fig. 2b). This is because logging roads and open clearcut areas emit rather than sequester carbon and further reduce sequestration on adjacent areas through edge effects. Recently, Duncanson et al., (2023) used extensive spaceborne measurements from NASA’s GEDI mission to demonstrate that protected areas are effectively sequestering a lot more CO_2 from the atmosphere than otherwise similar but degraded areas that surround them. *Ceteris paribus*, a loss of this carbon sequestration capacity drives up atmospheric GHG concentrations in the same manner as a new source of emissions. As such, forgone sequestration is often considered an indirect form of GHG emissions. Maxwell et al. (2019) found that accounting for forgone emissions and edge effects from intact tropical forest loss in the 2000s increased the net carbon impact sixfold over the estimate based on forest clearance alone.

Industrial logging activities also generate significant GHG emissions associated with construction of logging roads, operation of logging equipment, fertilizer and pesticide applications, milling and manufacturing, transport of logs and end use products, and disposal of wood products in landfills. CO_2, CH_4 and N_2O are emitted by these processes (Hudiburg et al., 2019; Law et al., 2018; Miner and Perez-Garcia, 2007). The whole process can be thought of as a “catch and release” forest carbon regime.

GHG emissions are not the only climate concern about industrial logging practices. This is because lands dominated by clearcuts, dense networks of logging roads, and timber plantations exacerbate stressors that are already being intensified by climate change. For example, wildfires that burn in complex natural forests create a mosaic of intensely burned and relatively untouched areas while wildfires that burn in homogenous tree plantations are more likely to be uniformly severe (Evers et al., 2022; Stone et al., 2008). Surface temperatures in open clearcuts can reach extreme levels, often 20 °C above ambient temperatures in surrounding forests (Hungerford & Babbitt, 1987). Paired watershed studies in Oregon show that heavily logged watersheds deliver 50% less dry season water

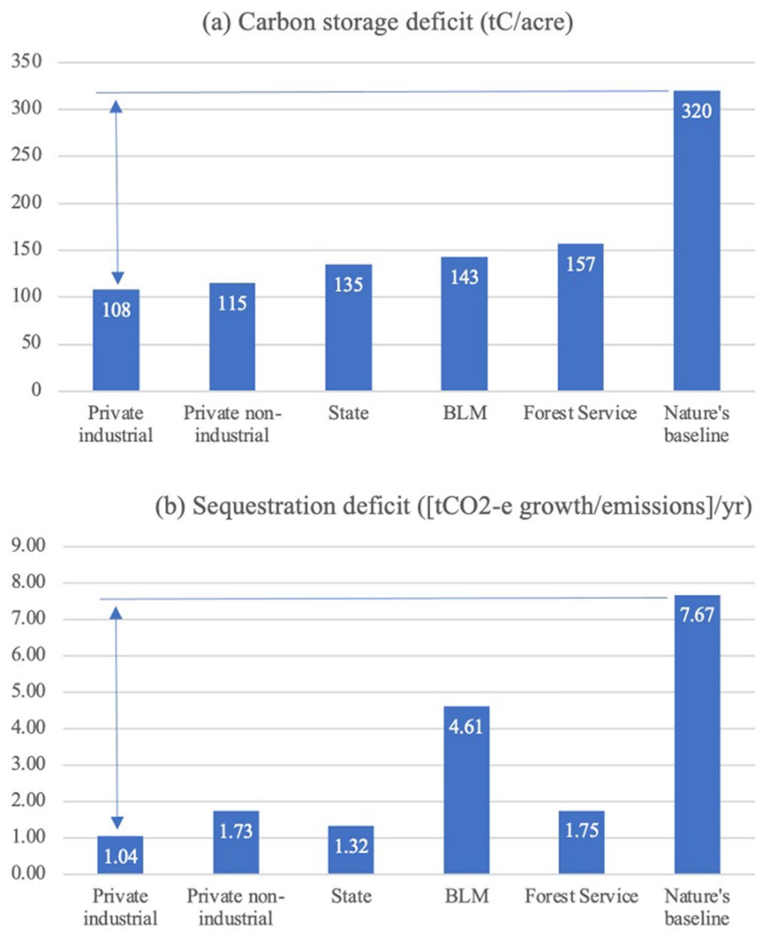

Fig. 2 Carbon storage and sequestration deficits—western Oregon 2000–2016 averages. Panel **a** equates nature's baseline with carbon stored in remnant old growth stands (Seidl et al., 2012). Carbon density by ownership from USDA Forest Inventory and Analysis data. Panel **b** presents the ratio of carbon intake (growth) vs. emissions via harvest and mortality. Nature's baseline estimated from FIA data on unharvested Bureau of Land Management (BLM) tracts

than the natural forests they've replaced (Segura et al., 2020). On the flip side, clearcutting drives up extreme peak flows-up to 330% above natural rates—during flooding events (Eisenbies et al., 2007).

For these reasons, the evolving climate policy framework is geared toward halting deforestation and forest degradation and replacing conventional industrial practices with climate smart alternatives with the overall goal of restoring natural forest conditions to as much of the forested landscape as possible. The Glasgow Leaders Declaration on Forests and Land Use seeks an end to deforestation and forest degradation by 2030, while in the US, initiatives such as Executive Orders 14008 (2021) and 14072 (2022) seek to significantly scale up climate smart forestry alternatives. Although the concept of climate smart is far from settled, ideally such alternatives would result in simultaneous advancement of four key goals relative to business as usual: reducing logging-related emissions, increasing carbon stored on the land, increasing landscape level sequestration and making the land less vulnerable to climate change. Practices such as long harvest rotations, variable density plantation thinning, establishment of strategic forest carbon reserves, afforestation, proforestation (allowing forests to grow to their maximum ecological potential) are among practices that fit these general goals (Law et al., 2021; Bai et al., 2020; Moomaw et al., 2019; Law et al., 2018; Pukkala, 2018). A forest carbon tax and reward program can accelerate adoption of these practices while working in tandem with other market-based approaches, such as voluntary and regulatory offsets, cap-and-trade, and subsidy reform.

3 Forest carbon tax and reward – design options

There are many alternative configurations of a forest carbon tax and reward program that can be implemented at the national or subnational level, but the three most salient features include a tax on the GHG emissions associated with conventional logging practices to put a price on the climate change externality, credits and exemptions to incentivize good practices, and use of tax proceeds to help forestland owners make the transition to climate smart alternatives. Liu and Wu (2017) considered the first and third features in their study of a forest carbon tax approach in China, and in Oregon, a legislative vehicle to operationalize a program with all three features was drafted for consideration during the 2017 legislative session. Below, we consider how such a program could be operationalized with respect to decision points common to carbon tax proposals for fossil fuel emissions (Parry et al., 2015).

3.1 Regulated entities

Unlike many demand side carbon tax proposals, the most efficient target for a forest carbon tax is at the point of resource extraction since once a site is logged a chain of downstream GHG emissions is irreversibly committed, as are damages to climate resiliency. It is also the leverage point for inducing on-the-ground changes to forest management. As such, forestland owners who conduct intensive logging activities would be the regulated class. In the US, states have discretion to impose logging-related carbon taxes on any forestland owner, including federal agencies under their Clean Air Act (42 U.S.C. §7401 et seq.) authority. However, it may be more optimal to limit a forest carbon tax to large, corporate forestland owners since in the US, they are the most significant sources of both emissions and threats to climate resiliency. This includes corporate owners who have acquired forestlands for development purposes. These owners account for 33% to 66% of timber volume harvested in the four states we address (Table 1).

In general, landscapes managed by non-industrial forestland owners are more diverse, and many owners are already managing these lands with climate smart practices. These lands also support the single largest share of carbon rich mature forests across all US ownerships (DellaSala et al., 2022).

3.2 Scope of taxable emissions

GHG emissions associated with the logging and wood products process are both biogenic and fossil fuel related and are released over an extended period as end use products oxidize, decay and are discarded. For this reason, life cycle analysis (LCA) should be used as

Table 1 Forestland ownership and annual timber harvest (see Online Resource 1 for sources)

	Oregon		Washington		Maine		North Carolina	
Forestland ownership	(Ha)	%	(Ha)	%	(Ha)	%	(Ha)	%
Federal	7,205,439	60.16	3,942,049	44.11	104,004	1.47	842,557	11.10
State	385,261	3.22	994,719	11.13	501,406	7.08	340,746	4.49
County and municipal	87,412	0.73	188,179	2.11	85,389	1.21	108,861	1.43
Tribal	200,724	1.68	764,048	8.55	95,506	1.35	10,117	0.13
Private industrial (or large)	2,682,261	22.39	1,960,705	21.94	4,032,294	56.93	1,896,360	24.98
Private non-industrial (or small)	1,416,402	11.83	1,086,178	12.16	2,264,624	31.97	4,392,465	57.86
Total	11,977,499	100.00	8,935,877	100.00	7,083,224	100.00	7,591,105	100.00
	Oregon		Washington		Maine		North Carolina	
Timber harvest	m^3	%	m^3/yr	%	m^3/yr	%	m^3/yr	%
Federal	1,176,657	12.85	328,680	5.09	5,706	0.10	54,018	0.63
State	717,899	7.84	1,633,730	25.74	127,254	2.23	196,575	2.31
County and municipal	104,388	1.14	37,028	0.57	48,505	0.85	3,997	0.05
Tribal	21,060	0.23	420,100	6.50	–	–	-	–
Private industrial (or large)	6,027,965	65.84	2,699,452	41.77	1,884,274	33.02	4,764,208	56.00
Private non-industrial (or small)	1,107,981	12.10%	1,314,098	20.33%	3,640,723	63.80	3,488,716	41.01
Total	9,155,950	100.00	6,463,089	100.00	5,706,462	100.00	8,507,514	100.00

a framework for assigning an emissions charge at the point of harvest. Standard practice for LCAs used in carbon offset markets is an accounting period of 100-years, and this is also the time frame used in look-up tables that estimate carbon stored in long-lived wood products produced in the US as they decay or are discarded (Smith et al., 2006). Options include limiting the carbon tax to biogenic sources or applying the tax to both biogenic and fossil fuel related sources. Rationale for the former is that fossil fuel related emissions may already be regulated via other climate policies and programs.

3.3 Tax mechanism

To minimize regulatory burdens, the levy could take the form of an increment to existing severance or excise taxes on each thousand board feet (mbf) harvested, which many state governments already have in place. Current rates in Oregon, Washington, and North Carolina range from \$0.40–\$12.45 mbf^{-1}. A carbon charge would be added based on the product of the forest carbon tax rate adopted (\$ tCO_2-e^{-1}), and an adjustable emission factor (tCO_2-e mbf^{-1}) derived from state-level emissions inventories (demonstrated below). Adjustable emission factors could be adopted through rulemaking, and periodically updated as new or improved information becomes available.

Volume destined for long-lived wood products could have an emission factor lower than volume destined for pulp, paper, or biomass markets, and state agencies could also publish a reduced emission factor on volume harvested from thinning operations as these have lower effects on forgone sequestration. The emission factor associated with forestland conversion could be higher since forgone sequestration would be permanent. Finally, the emission factor could be adjusted based on ecological region(s) of timber harvest, which often have significant differences in the density of carbon stored at a logging site and rates of carbon sequestration. To determine a given taxpayer's liability, these emission factors would be applied to harvest and land use conversion data supplied by each industrial forestland owner each year and adjusted up or down depending on the share of reported harvest volume being diverted to long-lived or short-lived products and the volume extracted in association with logging roads or development. Much of the information needed to adjust the tax rate up or down for a given forestland owner's harvest in a given year is already reported to states in association with timber harvest notifications and/or permits as well as quarterly harvest tax returns (See Online Resource 1 for links to relevant forms). As such, state agencies would face a relatively light workload associated with gathering the tax and should only need a minor share of tax revenues for administration.

3.4 Tax rate

As an environmental (Pigouvian) tax, ideally, the tax rate would be based on the social cost of carbon (SCC), a figure that varies widely in the literature but nonetheless can be adopted by each state through rule making processes. The current US federal rate is roughly \$51 tCO_2^{-1}, but there is a nearly universal agreement that the true costs are significantly higher. There is also the possibility of using a state-level SCC—one that considers only in-boundary emissions and climate change costs, especially those related to climate adaptation. Developing a reliable stream of funding for climate adaptation is, in fact, one of the primary purposes of most carbon pricing schemes, including carbon taxes (Heine et al., 2019; Seo, 2009).

3.5 Exemptions and credits against the levy

To incentivize climate smart practices, corporate owners could be given several options for reducing the tax burden. One way is to credit CO_2 absorbed by growth of stands that meet the permanence and additionality tests common to offset markets (Ruseva et al., 2017) such as permanent stream or wildlife habitat buffers that exceed legal requirements, forests set aside for non-timber uses, forests considered inoperable for voluntary reasons (i.e., uneconomical), or forests enrolled in third-party verified carbon storage agreements. Volume extracted from lands under such agreements could also be exempted from the tax. For forestland conversion, the credits could be structured along a similar path in order to incentivize greater retention of trees and forest patches within lands being developed for residential or commercial purposes.

3.6 Use of tax revenues—a forest carbon incentive fund

Following the general configuration of other environmental taxes, tax revenues could be deposited in a special fund used both to reduce the externality associated with conventional logging practices and to incentivize the transition to climate smart alternatives. Small forestland owners could be the exclusive recipient of rewards from this Forest Carbon Incentive Fund (FCIF), and rewards could take the form of carbon storage payments (which increase over time), market rate purchases of land or conservation easements, cost-share assistance for alternatives to clearcutting or other payments for ecosystem services. Payments for carbon storage are a form of pay for performance incentives that are more efficient than practice-based incentives since they preserve landowner flexibility to select the optimal pathway to achieving the desired environmental outcome (Talberth et al., 2015). Transaction costs involved—i.e., regular carbon stock inventories—could be fully borne by the state agency administering the FCIF.

The rationale for limiting FCIF payments to small forestland owners is the same for other cost-share or incentive programs exclusive to this owner class: small owners face a competitive disadvantage (Wise et al., 2019) relative to corporate owners who enjoy economies of scale and more capacity to capture public funding from a variety of sources. Small forestland owners also tend to have much higher levels of forest carbon storage but are excluded from carbon markets since forests with little or no existing logging pressure cannot meet the additionality test of most carbon credit protocols.

4 Multistate analysis—materials and methods

Environmental taxation is not an exact science – it is replete with uncertainty over the level of target pollution, marginal damages, and how regulated entities would respond. All these sources of uncertainty are relevant to a forest carbon tax. Nonetheless, we believe the quality and accessibility of information needed to maintain GHG emissions profiles of the logging and wood products sector and derive emission factors needed to implement such a tax now exist. To demonstrate, we applied a replicable framework using four US states (OR, WA, ME, NC) as examples. Materials and methods for this analysis are described below, with data and calculations provided in Online Resource 2. In addition, to estimate potential tax revenues and effects of the tax on timber supply and forestland investment, we developed a preliminary cash flow model of a representative forestland investor in western Oregon based on emission factors calculated by the first analysis. This section also discusses materials and methods related to the cash flow analysis, with data and calculation details provided in Online Resource 3.

4.1 Logging emissions and adjustable emission factors

For each state, a conservative tally of the direct and indirect GHG emissions released or committed in association with annual logging activities can be approximated by the following:

$$\mathrm{GHG}hvt\,\mathrm{yr}^{-1} = (\mathrm{REM} - \mathrm{STOR}) + \mathrm{DR} + \mathrm{FS} + \mathrm{SA} + \mathrm{SL} \tag{1}$$

where GHG*hvt* yr^{-1} = Average annual GHG emissions (tCO_2-e) released and committed in association with timber harvest and land use conversion. REM = CO_2-e removed from forestlands by logging and land use conversion. STOR = Weighted average share of REM retained in harvested wood products or landfills at 100 years. DR = CO_2-e released from decay and combustion of logging residuals. FS = Forgone sequestration associated with logging roads, clearcut units, and land use conversion. SA = GHG emissions associated with silviculture activities. SL = GHG emissions associated with soil loss and degradation.

For reasons discussed in Sect. 3.2, we do not include downstream emissions from energy use during transport and manufacturing. Adjustable (default) emission factors were derived by dividing the results of Eq. 1 by average annual timber harvest volume and were further refined up or down in each state to account for different harvest purposes (wood products vs. land use conversion) and wood product end uses (short and long-lived product pools) by varying assumptions for STOR and FS.

4.1.1 *CO_2-e removals (REM)*

The most ubiquitous and accessible source of information for this adjustment is the US Forest Service's Forest Inventory and Analysis (FIA) program, which relies on a hexagonal network of inventory plots located on US forestlands at a density of roughly one plot per 2430 ha (Brand et al., 2000). Each state has an inventory cycle that completes roughly every five years. For our analysis, we used the web based *EVALIDator* application to extract information on annual growth, mortality, and harvest removals. *EVALIDator* is a US Forest Service online tool for accessing and analyzing data from the FIA program (USDA, 2022). Online Resource 2, Table 1, displays the data. To calculate REM, we multiplied dry short ton removals by 0.5 (carbon content), by 0.9072 to convert short to metric tons, and then by 3.67 to convert carbon to metric tons CO_2-e. While there are more precise methods available, this conversion process is the international standard (Deheza & Bellassen, 2010).

4.1.2 Long term storage in wood products and landfills (STOR)

This adjustment calculates the share of REM likely to be stored long term (100 years) in both wood products in use and landfills. Despite the sustainability challenges presented by ever-expanding landfill footprints, standard GHG accounting protocols fail to distinguish between the two with respect to long term carbon storage. For each state, annual timber harvest (tons) was distributed into four distinct product classes based on periodic timber output profiles: (a) softwood long-lived wood products (SW-LL); (b) softwood short-lived wood products (SW-SL); (c) hardwood long-lived wood products (HW-LL), and (d) hardwood short-lived wood products (HW-SL). REM was then allocated to each product class based on these shares and then multiplied by long term storage factors published in convenient look-up tables by Smith et al. (2006), which, despite refinements in several states, remain the most ubiquitously used data for estimating STOR.

4.1.3 Decay of logging residuals (DR)

Regional studies of post-harvest NEP can be used as a basis for estimating emissions from the decay of logging residuals following annual timber harvesting activities. NEP is typically expressed in grams carbon per square meter per year and remains negative (a source of emissions) for a period of time that varies with species, stand age, and type of harvest. For Oregon and Washington, we incorporated values from Turner et al., (2004), Grant et al., (2007) and Law et al., (2001) for even-aged treatments both east and west of the Cascades. For Maine, we used values based on Scott et al. (2004) for shelterwood harvests. For North Carolina, we used estimates from Johnsen et al. (2014) for even-aged harvesting of pine and Peckham and Buongiomo (2012) for hardwoods. These studies measured or predicted post-harvest emissions of 0.50–4.65 tC ha^{-1} yr^{-1} averaged over 13 years. DR for each state was calculated by multiplying the appropriate regional values by the rate of harvest (ha yr^{-1}) and then by 13. To be conservative, and except for shelterwood harvests in Maine, we only applied the DR calculation to harvest activity that resulted in tree cover loss, as measured by Hansen et al., (2013 – 2021).

4.1.4 Forgone sequestration (FS)

Presently, the standard convention is to exclude forgone sequestration from GHG accounting since it is not a direct emissions source. But as noted in Sect. 2 and by Maxwell et al. (2019), loss of carbon sequestration capacity has the same effect of raising GHG concentrations in the atmosphere as a direct emissions source and as such is an important factor to consider in a forest carbon taxation program. Ideally, FS would be based on the difference between the amount of carbon sequestered and stored on the land with and without logging over a specified time period, such as a harvest cycle. However, this would necessitate some rather complex modeling of growth and mortality. A more tractable, and conservative approach would be to limit the calculation to the period of negative NEP adopted for DR since net sequestration during this period is entirely absent. This was the method adopted for our demonstration. For each state, pre-harvest NEP was estimated from a combination of local studies and FIA data. For harvest activities, FS is simply the product of pre-harvest NEP and the presumed period of zero net carbon accumulation, or 13 years for this study. For land use conversion, we followed protocols inherent to offset markets and modeled FS over a 100-year period.

4.1.5 Silvicultural activities (SA)

Fossil fuel emissions from silviculture activities (SA) include those associated with harvesting, chemical and fertilizer applications, replanting, thinning, and road maintenance. For this analysis, we applied an emission factor from Sonne (2006) – 8.60 tCO_2-e ha^{-1} – to reported and estimated annual harvest acreage in OR, WA, and NC. The WA State Department of Natural Resources also uses this figure. For Maine, we adjusted this factor down to 7.14 tCO_2-e ha^{-1} to account for state-specific estimates of GHG emissions from forest harvesting alone, which accounts for roughly 60% of the SA total (Oneil & Puettmann, 2017). In addition, we estimated annual N_2O emissions from forest fertilizers by multiplying annual acreage treated by the rate of application (kg ha^{-1}) and then by an emissions factor (4.3% by weight) reported by Harris et al. (2022). To convert to CO_2-e, N_2O emissions were multiplied by a factor of 298 to account for the greater global warming potential of this gas.

4.1.6 Emissions from soil loss and degradation (SL)

While data on soil organic carbon (SOC) loss from timber harvesting are quite extensive and consistent, the fate of this carbon remains quite uncertain. However, it is widely accepted that a significant portion is emitted, while the rest redistributed over the land, in channels, or at sea. As a placeholder value, we used SOC loss factors of 22% and 36% for intensive harvest of softwoods and hardwoods from Nave et al. (2010) and Achat et al. (2015) as well as a lower bound emissions estimate of 15% of SOC from Lal (2020). To be conservative, we only estimated SOC loss from harvest acres that resulted in forest cover loss. Data on pre-harvest SOC stocks were extracted via *EVALIDator* for each major ecological region in each state. As previously discussed, post-harvest emissions may also include fluxes of CH_4 and N_2O associated with waterlogging and soil disturbance (Vestin et al., 2020), but methods to account for these emissions are not readily available and so are not included here.

4.2 Tax effects – representative forestland investor model for western Oregon

A general equilibrium analysis of tax impacts is beyond the scope of this paper. However, as an initial step, it is useful to consider effects of the tax on the profitability of investments in industrial timberland as an asset since a large and growing share of forestlands are now managed by investor-driven entities such as Timber Investment Management Organizations and Real Estate Investment Trusts (Sass et al., 2021).

To do this, we completed a net present value (NPV) analysis of a representative industrial timberland owner acquiring 100,000 acres (40,486 ha) of prime forestland in Oregon's Coast Range with and without the tax. In Excel, we modeled cash flows, NPV, and internal rate of return (IRR) from timber and carbon over 50 years and included land acquisition costs as well as the opportunity costs of capital (OCC) to reflect tradeoffs an investor faces when considering acquisition versus the next best alternative use of investment funds. NPV is generally recommended as being the preferred criterion in forest economics settings (Brealey et al., 2008; Klemperer, 2003; Wagner, 2012). IRR is most useful as an investment comparison tool when the implied cost of capital is included (Cubbage et al., 2014).

Physical data on forest composition, growth, harvest and carbon were extracted from *EVALIDator*, which allows users to specify a longitude, latitude, and radius for analysis. We chose a location and radius that encompassed 40,486 hectares of private forestland. We utilized growth and yield curves for coastal Douglas fir, the dominant commercial species. Land acquisition costs were based on recent transactions of large, industrial parcels in the area. Delivered log prices and timber management costs were derived from a variety of local sources, but most importantly Diaz et al. (2018) updated to current dollars. Finally, an estimate of carbon project development costs and revenues was supplied by a major carbon project developer. Three scenarios were modeled: (A) a baseline, no tax, scenario for comparison purposes; (B) pay and pass on, where the landowner pays half of the tax and passes on the rest, and (C) carbon market, where the landowner reduces their tax burden by participating in a voluntary offset agreement, doubling the size of stream buffers, partitioning the land base into conventional vs. long rotations and limiting harvest to 50% of growth. All scenarios were modeled with an OCC of 7% and a discount rate of 3% (standard in the US for benefit–cost and regulatory impact analyses), but we also tested the results against alternative rates. Detailed model specifications appear in Online Resource 3.

5 Results and comparison to previous work

Results of the four-state taxable emissions model, emission factors, and the representative forestland investor analysis are described below along with comparisons to prior results in the US and internationally.

5.1 Taxable emissions estimates

Table 2 presents our estimates of annual GHG emissions attributable to industrial logging and deforestation in the four states, excluding important downstream sources from transportation and wood products manufacturing. Estimates range from 22 to 57 Mt CO_2-e yr^{-1} and include both biogenic and non-forest fossil fuel related emissions, as well as emissions released or committed over 100 years. Emissions from decay and disposal of harvested wood products (REM-STOR) are the largest share in each state, while forgone sequestration (FS) is the second most impactful in OR, WA and NC. Interestingly, in Maine, FS is significantly lower due to the prevalence of shelterwood harvest and lower rates of carbon sequestration. Decay of logging residuals, silviculture activities, and soil loss represent about 18–24% of statewide totals.

In Oregon and Washington, our statewide emission estimates are almost identical to those modeled by Law et al. (2018) and Hudiburg et al. (2019) less forgone sequestration, which was not included in either of those analyses. For North Carolina, our estimate (57.19 Mt CO_2-e yr^{-1}) is significantly higher (+ 13 Mt CO_2-e yr^{-1}) than Talberth et al. (2019) primarily due to increased logging activity since that older study, inclusion of forgone sequestration attributable to land development and inclusion of emissions associated with silviculture activities and soil loss.

Table 2 Average annual emissions and adjustable emission factors associated with logging and deforestation. Forest carbon tax revenue projections are based on data from the representative forestland investor model

	Oregon	Washington	Maine	North Carolina
GHG emissions (tCO2-e/yr)				
Carbon removed by logging (REM)	38,343,040	33,184,688	18,552,669	38,576,131
Long-lived HWP storage (STOR)	− 14,328,359	− 11,639,257	− 4,754,979	− 9,232,243
Decay of logging residuals (DR)	9,633,000	8,348,600	3,610,527	8,623,462
Forgone sequestration (FS)	11,837,918	14,552,324	3,373,456	17,460,904
Silviculture activities (SA)	645,000	559,000	931,315	642,477
Soil loss and degradation (SL)	942,296	836,101	741,144	1,114,602
Total taxable emissions tCO_2-e/yr	47,072,895	45,841,455	22,454,131	57,185,332
Emission factors				
AEF tCO_2-e/mbf (Mg C/m^3)	12.13 (1.40)	16.74 (1.93)	9.29 (1.07)	15.86 (1.83)
EF-LL tCO_2-e/mbf (Mg C/m^3)	11.83 (1.37)	16.13 (1.86)	8.82 (1.02)	14.11 (1.63)
EF-SL tCO_2-e/mbf (Mg C/m^3)	15.04 (1.74)	20.00 (2.31)	9.85 (1.14)	15.97 (1.84)
EF-CONV tCO_2-e/mbf (Mg C/m^3)	9.08 (1.05)	11.42 (1.32)	7.89 (0.91)	11.02 (1.27)
EF-CONV tCO_2-e/acre (Mg C/ha)	429.49 (289.06)	429.00 (288.73)	163.00 (109.70)	442.50 (297.81)
Potential tax revenues				
Tax revenue scenario A ($million/yr)	$345.90	$213.70	$82.75	$357.42
Tax revenue scenario B ($million/yr)	$233.61	$144.33	$55.89	$241.40

5.2 GHG emission factors and an illustration of their application

Across the four states, adjustable (default) emission factors (AEF) range from 9.29 to 16.74 tCO_2-e mbf^{-1}. This is consistent with the range of values (7.5 to 17.8 tCO_2-e mbf^{-1}) calculated or inferred from previous studies in OR, WA, and NC less forgone sequestration (Hudiburg et al., 2019; Law et al., 2018; Talberth et al., 2019). Washington's AEF is greater because of a greater share of logging associated with development (~6072 ha yr^{-1}) and high rates of forgone carbon sequestration associated with loss of coastal rainforests. Table 2 also presents emission factors for long-lived and short-lived wood products that are derived by putting all harvest related removals in these baskets one at a time. On a cubic meter basis (1.05 to 2.31 Mg C m^{-3}), emission factors align almost perfectly with the range (0.99 to 2.33 Mg C m^{-3}) reported by Pearson et al. (2017) in studies of deforestation and forest degradation across 74 developing countries. The consistency of such volume-based GHG emission factors suggests that market-based interventions to track and regulate wood products emissions would rest on a solid empirical basis and could be applied broadly across the roughly one third (Puettmann et al., 2015) of global forestlands subject to commodity-driven logging pressure.

In addition to emission factors for long and short-lived wood products, Table 2 presents two separate emission factors for land use conversion—one applied to timber volume removed and one applied to the area developed to reflect 100-year FS. It is useful to disaggregate the two since many development projects take place on recently logged over lands and do not require extensive harvesting. Table 3 provides a simple example to illustrate how these factors can be used as the basis for a forest carbon tax on land proposed for development.

Across the four states, a typical subdivision deforests about 8–12 ha and yields about 117 m^3 wood per hectare. Such a project in Maine, which is losing about 2100 ha yr^{-1} to development, could be expected to yield 1180 m^3 in timber volume and deforest over 10 ha for a 100-unit development with a land-to-building ratio of 3:1. Using emission factors from Table 2, taxable emissions would be 3940 tCO_2-e from logs and biomass removed ($A \times B \times C$) * 3.67 (which converts carbon to carbon dioxide) and 4074 tCO_2-e as a forgone emissions charge ($A \times D$) * 3.67. Under the program envisioned, the developer would earn carbon sequestration credits of 2970 tCO_2-e for land not affected by the building footprint

Table 3 Application of land use conversion emission factors (Table 2) in Maine to a typical subdivision proposal on productive forestland

Parameters	
A: Area deforested (ha)	10.12
B: Wood products yield (m^3/ha)	116.57
C: Emission factor harvest (Mg C/m^3)	0.91
D: Emissions factor conversion (Mg C/ha)	109.70
E: Land-to-building ratio	0.66
F: Open space seq. rate (Mg C/ha/yr)	1.21
G: Tax rate (\$/tCO2-e)	\$51
Tax derivation	
H: Gross CO_2-e emissions $(A \times B \times C) + (A \times D) \times 3.67$	8015
I: Open space credit $(A \times E \times F) \times 100$ x 3.67	2970
J: Net CO_2-e emissions (H–I)	5045
K: Tax liability (J × G)	\$257,295

at sequestration rates that are typical for non-forested open space in the region. At a forest carbon tax rate of \$51 tCO_2-e^{-1}, the tax paid on net emissions (5045 tCO_2-e) would be \$257,295. To put this in context, the average profit margin found by Mohamed (2010) for similarly sized subdivisions in a neighboring state were just over \$1 million USD (\$1.4 million in 2023 dollars). While not excessive, a tax levy of this proportion (~20% of profits) would certainly help steer development pressure away from productive carbon sinks and incentivize climate smart practices such as natural stormwater controls, impervious pavement, tree retention, green space preservation and reduced building footprints.

5.3 Representative forestland investor model for western Oregon

With respect to the representative forestland investor model (Table 4), our results suggest that if designed along the lines suggested here, a forest carbon tax would help reduce logging pressure, maintain forestland as an attractive investment, and provide a strong incentive to enroll in carbon markets or otherwise adopt climate smart practices. The baseline, no tax scenario yields a 50-year NPV of nearly \$600 million off an initial investment of \$216 million and an IRR of 7.37%. This is firmly within the range (3.2 –10.0%) reported by Chudy and Cubbage (2020) for US timberland investments, excluding land acquisition costs, which can reduce IRR by 3–8%. Under the pay-and-pass-on scenario, a forest carbon tax is levied on 33% of volume harvested, which represents the excess volume harvested if the policy target was to increase rotation age from 40 to 60 years. The forestland owner would pay an effective tax of \$75.35 m^{-3} on total volume removed, which would generate about \$12 million per year in payments to a Forest Carbon Incentive Fund (FCIF). Half the tax burden would be passed on to downstream mills, raising delivered log prices from \$350 to \$388 m^{-3} and reducing demand by a comparable amount (~11%) if demand

Table 4 Representative forestland investor model (OCC at 7%, 3% discount rate, 50-year period)

	Scenario A Baseline (no tax)	Scenario B Pay and pass on	Scenario C Carbon market
Fully operable area (ha)	36,966	36,966	27,782
Annual yield (mbf)	73,774	65,844	53,267
Annual yield (m^3)	174,085	155,372	125,694
Delivered log price (\$/mbf)	\$827	\$916	\$873
Delivered log price (\$/m^3)	\$350	\$388	\$370
Total investment costs (\$million)	\$216.08	\$216.08	\$216.08
Opportunity cost of capital (\$million/yr)	\$15.66	\$15.66	\$15.66
Mgmt. and harvest costs (\$million/yr)	\$22.32	\$17.31	\$14.31
Effective carbon tax (\$/mbf)	\$0.00	\$177.80	\$60.51
Effective carbon tax (\$/m^3)	\$0.00	\$75.35	\$25.64
Carbon tax payments (\$million/yr)	\$0.00	\$11.71	\$3.22
PV timber income (\$million)	\$1569.80	\$1551.67	\$1213.08
PV carbon income (\$million)	\$0.00	\$0.00	\$47.49
PV cost stream (\$million)	\$977.26	\$1,149.61	\$853.96
Net present value (\$million)	\$592.54	\$402.06	\$406.61
Internal rate of return (%)	7.37%	3.86%	4.68%

elasticity were close to neutral. Annual harvest volume would decrease from 174 to 155 Mm^3 which effectively increases the rotation age to about 44 years rather than 40. This, in turn, increases yield per acre (longer harvest rotations mean bigger trees) and lowers overall harvest costs somewhat since the same volume could be produced from fewer acres harvested. NPV declines to $402 million, while IRR is reduced to 3.86%.

Participation in carbon markets would improve the investment's performance relative to the pay-and-pass-on scenario. While overall volume harvested would not exceed 50% of growth (here, this translates into ~ 126 Mm^3 yr^{-1}), the forestland owner would enjoy substantial (~ $48 million) early period carbon payments. Volume removed from the long rotation partition would be exempt from the tax, and the forestland owner would earn sequestration credits by doubling the size of buffers required along streams and near protected resource sites. Effective carbon tax payments on all volume removed would drop to $25.64 m^{-3}, resulting in annual tax payments of $3.2 million to the FCIF. The forestland owner, as before, would pass on about half of this cost downstream, resulting in delivered log prices of $370 m^{-3}. NPV would rise slightly to $407 million, and IRR would increase to 4.68%, inclusive of land costs (without land costs the modeled IRRs for both scenarios would range from 6.86 to 12.68%). These results suggest that under either the pay-and-pass-on or carbon market scenarios, forestlands would remain an attractive investment, especially to patient capital investors like family offices, pension funds, NGOs and sustainability fund managers who generally seek IRRs in the 5–9.9% range over extended time horizons and prioritize investments with full internalization of social costs (NatureVest, 2014).

As for FCIF revenues, Table 2 presents two stylized scenarios. In Scenario A, two thirds of industrial forestland owners in each state would adopt the pay-and-pass on option and one third would choose the carbon market option. Under Scenario B, the situation is reversed. After adjusting for overall reduction in volume harvested, the scenarios predict annual tax revenues of $56 to $357 million paid into state forest carbon incentive funds. Without a general equilibrium analysis, these figures remain just informed guesswork. But funding at this level, which is certainly plausible, could help states move the forest-climate agenda forward in major ways. In Oregon, a FCIF capitalized at $346 million per year (Scenario A) could, in one year, enroll 100,000 ha of non-industrial private forestlands in a carbon payment program that would pay landowners $7.70 $tCO_2\text{-}e^{-1}$ and protect nearly 42 million tCO2-e over 30 years at a program cost of $320 million (Graves et al., 2022). In Maine and based on cost data supplied by local land trusts, Scenario B would generate about $56 million annually, enough to protect 60,729 ha a year with conservation easements that preclude commercial or residential development. And in North Carolina, the minimum annual FCIF capitalization of $241 million would be enough to achieve afforestation on about 117,409 ha a year out of 1.52 million ha identified as being ripe for doing so (Fuller & Dwivedi, 2021; Wade et al., 2019). While in practice, FCIF revenues would not be allocated to a single purpose, these examples illustrate the kinds of big-ticket items that could be funded by a well-designed forest carbon tax program.

6 Conclusions and future research

Carbon taxes are an efficient option for regulating greenhouse gas emissions and generating funding to invest in adaptation and low-carbon alternatives. Here, we investigate the feasibility of a forest carbon tax to reduce emissions from deforestation and forest degradation and spur investments in climate smart forestry need to achieve global ambitions such as the Glasgow Leaders Declaration and several Sustainable Development Goals, including SDG 1 (reducing climate risks), SDG 13 (climate action) and SDG 15 (sustainable land management). In this paper, we identified key design features of a forest carbon tax program that could be implemented at the subnational level in regions with robust logging sectors. The program would rely on periodic inventories of GHG emissions associated with industrial logging practices, including those associated with land use conversion, adjustable GHG emission factors applied to taxable volume harvested and area developed, and an estimate of the social cost of carbon. Tax revenues would capitalize a Forest Carbon Incentive Fund paid out to small landowners to scale up enrollment in third-party verified long term carbon storage agreements and to establish lasting protection for native, mature, and old growth forests. As demonstrated here, we believe the methods and sources of information available to establish such a program are well-within reach of state agencies in the US and their counterparts abroad and the tax itself could be implemented with little additional administrative costs if it piggybacks on existing severance or excise tax programs.

Future research is needed to improve emissions estimates from several of the sources discussed here—especially soil loss and forgone sequestration—and to gauge the effects of such taxes on timber supply, tax revenues, and forestland investment through a general equilibrium model and more complete analysis of cash flows, NPV and IRR. Given the magnitude of social and environmental impacts associated with industrial logging and deforestation it seems prudent to further examine what a forest carbon tax could achieve to reduce such impacts while advancing multiple sustainable development goals.

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Data availability The data collected and materials for analysis are included with the manuscript. The corresponding author is ready to clarify the data or analysis methods on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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