Forest Policy and Economics 187 (2026) 103784

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Evaluating carbon additionality under short-term harvest deferrals in U.S. southern plantation forests

Bruno Kanieski Da Silva[a,*], Jesse D. Henderson[b], Shaun M. Tanger[d], Andrew R. Tilman[e], Stephanie Chizmar[b], Rajan Parajuli[f], Mohammad Marufuzzaman[c], Christine C. Fortuin[g]

[a] Warnell School of Forestry and Natural Resources, University of Georgia, USA
[b] USDA Forest Service, Southern Research Station, USA
[c] Department of Industrial and Systems Engineering, Mississippi State University, USA
[d] College of Forestry, Agriculture and Natural Resources, Arkansas Center for Forest Business, University of Arkansas at Monticello, USA
[e] USDA Forest Service, Northern Research Station, USA
[f] Department of Forestry and Environmental Resources, North Carolina State University, USA
[g] Department of Forestry, Mississippi State University, USA

ARTICLE INFO

Keywords:
Agent-based model
Harvest policy
Carbon sequestration
Carbon additionality
Forest landowners
Harvest deferral
Nature-based offsets
Voluntary carbon market

ABSTRACT

The growing demand for nature-based solutions to mitigate climate change has heightened interest in forest carbon programs, particularly in the southeastern United States, a region with abundant forest resources. Challenges such as additionality, leakage and permanence requirements, and competition between timber and carbon markets are among the complexities of implementing effective forest carbon programs. This study examines the impacts of one-year harvest deferral programs on carbon sequestration and timber market dynamics using an agent-based simulation model. The model incorporates interactions between landowners, a wood-consuming mill, and a carbon credit developers. Through a simulation experiment, we explored varying levels of carbon demand and prices to analyze how forest landowners respond under different scenarios and to examine the outcomes for stand age structure, stumpage and delivered prices for timber, and carbon sequestration over a 100-year period. Results indicate that a one-year harvest deferral program has leakage effects, mainly on timber market dynamics by increasing stumpage prices and extending the rotation age. In addition, our model shows that this type of program can lead to additionality in scenarios with higher carbon demand but also higher program costs. Lastly, we observe permanence at the landscape level through an increasing and higher carbon volume than in scenarios without a carbon program, particularly at moderate carbon prices and higher levels of carbon demand. This study contributes to a growing literature by providing insights into economic and ecological trade-offs of forest carbon offset programs and their implications for sustainable forest management in the Southeastern US.

1. Introduction

Since the early 1990s, forest-based carbon sequestration has gained traction due to its relatively low cost and potential to contribute to international climate goals (Sedjo et al., 1995; Stavins and Richards, 2005; Griscom et al., 2017). Despite growing demand, led by a number of multinational corporations, such as Amazon, Microsoft, and others, supply of carbon for forest assets has lagged as many landowners have elected to not participate in carbon offset programs. A range of barriers are cited for the lack of participation on the part of landowners, such as legislative uncertainty, insufficient payments, withdrawal penalties, and long-term commitments that may discourage enrollment in programs such as California's cap-and-trade system or voluntary private initiatives (Tanger et al., 2022). One notable exception, the Natural Capital Exchange (NCX, formerly SilviaTerra), achieved significant national adoption in the United States before its cessation in 2024. By 2022, NCX had enrolled approximately 1.86 million hectares of forestland across 35 US states (Business Wire, 2022). Unlike most programs that require long-term commitments, NCX offered a unique model which utilized one-year harvest deferral contracts, with the option to renew annually. This program formed under the premise that providing a more accessible entry point for participation would encourage more forest suppliers to

* Corresponding author.
E-mail address: bruno.silva@uga.edu (B.K. Da Silva).

https://doi.org/10.1016/j.forpol.2026.103784
Received 14 August 2025; Received in revised form 16 March 2026; Accepted 10 April 2026
Available online 20 April 2026

engage in carbon offsetting, mitigating price concerns, and spurring more immediate gains in carbon sequestration and associated nearer term climate benefits.

However, short-term forest carbon deferral programs have faced criticism for their limited permanence due to brief contractual commitments and for enabling strategic participation by landowners, which can undermine the principle of additionality (Nova, 2024). Typically, crediting rules require forest-based carbon offsets to ensure that any project's activities, or carbon used to offset emissions, are maintained and managed on the site "permanently", often taken to mean at least 100 years (Parisa et al., 2022; Verra, 2013). Short-term projects necessitate the use of accounting techniques that show the comparable climate benefits given that they will not technically meet the 100-year commitment period from an individual credit perspective (or whatever period the verification standard requires to achieve permanence). Marland et al. (2001) make the case for a sort of permanence of short-term projects or *rentals* succinctly: "*Although any individual project may be temporary, the aggregate effect of economic incentives for carbon sequestration will be to increase aggregate sequestration on a permanent basis*" (p. 261).

While not exclusive to short-term projects, tonne-year accounting is used to quantify the climate benefit of temporary carbon storage by assigning partial credit for storing carbon for a limited time rather than permanently removing it from the atmosphere. It provides a way to measure and compare the impact of short-term sequestration projects relative to permanent offsets (Galik et al., 2022).[1,2] Currently, of the major US verification standards, only Climate Action Reserve (CAR) has tonne-year accounting incorporated into its methodologies. Specifically, CAR's Soil Enrichment Protocol and the Mexico Improved Forest Management Protocol include provisions for tonne-year accounting, allowing for the evaluation of carbon projects with varying durations, such as 30, 40, or 100 years. Globally, the only other Protocol is Quebec's Reforestation Protocol, which enables the bundling of short-term carbon storage into offset credits, facilitating the inclusion of temporary carbon forest offset projects. After a public consultation, Verra chose to pause incorporating tonne-year accounting into their Verified Carbon Standard (VCS) program—but did state that the decision could be revisited in the future (Verra, 2022).

Over the last decade, research on carbon markets has expanded rapidly alongside the growth of voluntary carbon programs (e.g., Mason and Plantinga, 2013; Tahvonen and Rautiainen, 2017), however, there remains a notable gap in rigorous analysis of whether harvest deferral initiatives satisfy key integrity standards—additionality, leakage, and permanence. Additionality refers to whether the carbon sequestered by a project exceeds what would occur under a business-as-usual scenario. Leakage refers to not only avoiding harvesting in one area which could trigger heavier harvesting in other areas, but also possible market effects like changes in prices, spatial allocation, and costs. Lastly, permanence addresses the durability of carbon storage over time, ensuring that credited carbon remains sequestered for decades rather than being quickly reversed.

Since a harvest deferral by one landowner might simply lead to another landowner harvesting instead causing a chain effect across the supply, this analysis requires a systemic viewpoint, modeling market interactions among various agents in the forest products markets alongside carbon program aggregators offering harvest deferral contracts. To evaluate the carbon outcomes of a one-year harvest deferral program, we set out three objectives: (1) Determine how interactions among forest landowners (suppliers) and a wood-using mill (consumer) change when carbon sequestration emerges as an alternative income source for landowners. (2) Assess whether one-year harvest deferrals offered to landowners lead to landscape-level additionality and permanence. (3) Evaluate leakage effects by analyzing changes in stumpage and delivered timber prices, forest age distribution, and procurement distances.

To address these objectives, we estimated forest carbon additionality by comparing total tonnes of CO2e under a baseline scenario without a carbon market to scenarios with varying carbon market sizes and prices. We then analyzed permanence and leakage through long-term simulations of timber market dynamics and spatial procurement patterns.

2. Background

The southeastern United States[3] has highly active timber markets, with landowners making forest management decisions based on a complex interaction between multiple landowners (supply) and wood-consuming mills (demand). About 95% of timber harvests in the southeastern United States come from privately owned forestland (Butler et al., 2022), and most of the large forest landowners in the region use forestland resources to maximize profit returns (Hodges et al., 2019). In addition, the majority of the wood-consuming mills no longer own their own timberland, procuring timber from heterogeneous market participants—either from small non-industrial private owners, also referred to as family forest owners, or institutional owners, such as corporations, Timber Investment Management Organizations (TIMOs) or Real Estate Investment Trusts (REITs) (Zhang, 2021).

With 83.77 million hectares of forestland (USDA Forest Service, 2023), the forest sector in the southeastern US was responsible for a direct Gross Domestic Product of $61.6 billion in 2023 (Arkansas Center for Forest Business, 2023). In addition, the current forest area provides a wide variety of ecosystem services such as improved water quality and quantity, soil stabilization, wildlife habitat, and carbon sequestration with substantial economic value. For example, in the state of Georgia the direct economic impact of the forest industry in 2018 was estimated to be $36.3 billion, while the non-timber and non-recreation ecosystem service value of forestland was estimated to be $37.6 billion (Georgia Forestry Commission, 2018).

While the southeastern US is an active marketplace, timber prices have decreased substantially over the past two decades due to a combination of inventory surplus and wood mill closures for small and large diameter timber harvest (Brandeis and Guo, 2016; Parajuli et al., 2016; Forisk, 2024; Dezember, 2018; Dezember and Monga, 2021). Lumber prices grew significantly in the region over the past decade; stumpage prices have stayed largely flat since the Great Recession (Parajuli et al., 2016; Lamichhane et al., 2025). Consequently, forest landowners and investors have looked for alternative income sources, such as provision of carbon offsets (Mei, 2023).

Planting trees and engaging in activities that promote tree growth effectively removes carbon from the atmosphere, storing it in both living and dead biomass. This process has relatively low costs and has attracted a number of investors and corporate customers (Trencher et al., 2024). For instance, in 2024, TotalEnergies (a French multinational energy company) purchased around $100 million in carbon offset credits from forestland, partially located in the southeastern US (Dezember, 2024). The search for this type of carbon offsets is projected to increase in the

[1] Tonne-year accounting is an approach used in carbon offsetting to measure and value the temporary storage of carbon in a system (e.g., forests, soils, or other carbon sinks). Unlike traditional carbon accounting, which typically assumes that carbon storage is permanent, tonne-year accounting recognizes that carbon sequestration is often temporary and quantifies the benefit of storing one tonne of carbon for a specific period.

[2] It is important to note that tonne-year accounting and short-term projects are often conflated in the public discourse. However, tonne-year accounting can be applied to longer-term projects. Galik et al. (2022) provide a thorough treatment of temporary forest carbon crediting.

[3] An area including eastern Texas and Oklahoma, Arkansas, Kentucky, Virginia, Louisiana, Tennessee, North Carolina, Mississippi, Alabama, Georgia, South Carolina, Florida.

upcoming years; the total demand for carbon offsets will reach 1.2 GtCO2e in 2030 and jump to 5.4 GtCO2e in 2050 (an increase of 450%) (BloombergNEF, 2023). According to Bloomberg, even though some of the carbon offset buyers might be sensitive to expected price increases, others have dedicated to net-zero targets and are set to augment their existing project commitments. Forestry and land use projects have the potential to fill a share of this demand.

Although forest-based carbon sequestration offers many benefits, some argue that dedicating land use to forest to sequester carbon leads to competition with food production (Monge et al., 2016), while others dispute this concern (Mihiar and Lewis, 2023; Henderson et al., 2024). Similarly, it is conceivable that wood-fiber prices could increase in the presence of harvest restrictions or deferrals, a typical approach in projects adopting forest-based carbon sequestration (Parisa et al., 2022; Tanger et al., 2022; Sartori et al., 2024). Even taking the purported permanence of deferral projects at face value (Marland et al., 2001; Parisa et al., 2022), an open debate persists about the extent to which forest carbon offset projects provide additionality and how sequestration changes dynamically across time and space in a timber market.

The literature to date has addressed the interaction between carbon and timber markets at multiple scales. With studies focused on stand and forest levels (e.g., Dong et al., 2021; Hernandez et al., 2014; Pingoud et al., 2018), and at global and regional scales (e.g., Austin et al., 2020; Buongiorno and Zhu, 2013; Daigneault et al., 2022; Baker et al., 2023; Guo et al., 2023; Wear and Coulston, 2015). Although these studies have enlightened the discussion about timber and carbon markets, their spatial scope is either narrow (single stand level harvest decisions) or broad (global and regional) as decision-making in private forest planning is typically done so at a wood-basin level, with one or more wood mills making fiber procurement decisions in concert with forest landowners.

To address this gap, several studies have examined related aspects of carbon offset integrity. For example, Mason and Plantinga (2013) investigated asymmetric information and additionality in carbon contracts; although the authors did not investigate the interaction with carbon, they did provide an overview of government incentives for carbon. Tahvonen and Rautiainen (2017) investigated the economics of forest carbon storage and the additionality principle; according to the authors, the principle of additionality does not cause great distortions on optimal rotation if prices and land-allocation are exogenous, otherwise there is a great movement far from optimal rotation and land allocation. Rossi et al. (2023) most closely captures wood basin level dynamics in forest offset markets with their examination of harvest deferral effects on timber market and carbon additionality in the state of Mississippi, USA, examining multiple US forest service ecoregions.

In this study, we contribute to current literature by developing an agent-based model that integrates the value of carbon storage into the calculation of Land Expectation Value (LEV) in pine plantations used for timber production. Contrary to a top-down optimization approach, we simulated multiple agents (landowners, mill, and carbon aggregator) to understand the impact of one-year deferrals on timber markets at the wood basin level. The simulation model is designed in such a way that each forest landowner agent engages in traditional timber harvesting to maximize their profits while exploring the potential for collaboration with a carbon program agent. The objective of this carbon program agent is to achieve a minimal carbon quota while enrolling landowners with the maximum likelihood of harvesting.

Our focus lies specifically on understanding landowner timber harvesting behavior, wherein landowner decisions are influenced by the demand from a wood-consuming mill for their timber and carbon market price incentives derived from a hypothetical aggregator that offers one-year deferral terms. This framework effectively allows the landowner to delay their harvest for one year, with additional years conditional on demand and supply conditions and specific attributes of their timberland. Our approach simulates interactions among landowners, a mill, and a carbon aggregator to capture timber market dynamics under one-year harvest deferrals. Specifically, the model enables us to: (1) analyze landowner harvesting behavior under competing timber and carbon incentives, (2) quantify economic and ecological trade-offs—including additionality, permanence, and leakage—across scenarios of varying carbon prices and demand for timber products, and (3) evaluate long-term impacts on stumpage prices, procurement distances, and stand age structure. These contributions provide a novel basin-level perspective on short-term carbon programs and their implications for sustainable forest management.

3. Simulation space assumptions

We parameterize the forest inventory information in our model based on data from the United States Department of Agriculture (USDA) Forest Inventory Analysis (FIA) program (USDA Forest Service, 2023). We investigate supply and demand interactions between three agent types in an agent-based modeling (ABM) approach that includes landowners, a single wood-consuming mill, and a single carbon aggregator. To capture the spatial and temporal dynamics of a timber market, we simulate a spatial distribution of 1423 landowners[4] within a 100-mile radius of a mill (Fig. 1A and B).

The model assumptions are as follows: (1) The wood-consuming mill, which conceptually includes a timber procurement team, minimizes costs by selecting the most affordable source of fiber (lowest delivered prices) among the landowners. (2) The mill does not request any specification of the diameter classes, accepting both large and small logs; hence, it consumes the entire volume from the clearcut operations. (3) We randomly assign an age to each stand ranging from 0 to 65 years old[4] and forest stand area ranging from ~16 to 202 ha[5] to each landowner (Fig. 1C). (4) We then integrate the stand ages with the yield curve developed by the Plantation Management Research Cooperative - UGA (PMRC) (Harrison and Borders, 1996) and calculate the total timber volume (only the main trunk – no branches nor roots) available by landowner for an even-aged managed pine plantation forest (Fig. 1D and E). (5) Last, we calibrate the demand for timber by multiplying the total inventory volume in the market by a removal/inventory ratio of 4% (Fig. 1F). For example, the total inventory volume in year one is approximately 45.35 million tonnes of green wood, thus the demand was 1.81 million tonnes annually across the simulation period (43.35 million tonnes times 4%).

We kept the demand for timber and carbon held constant under deferral contracts constant over time as an experimental control to isolate the effect of introducing a carbon market on timber prices, stand age structure, and carbon sequestration. By holding demand constant within each scenario, we ensured that any changes in stumpage prices, procurement distances, and forest age distribution were driven solely by supply-side adjustments and competition between timber and carbon markets. This strategy also reflects the short-term rigidity of industrial wood demand, which is often tied to mill capacity and long-term contracts rather than immediate price signals.

Because carbon markets lack transparent and consistent reporting on prices and demand—particularly for forest-based assets—we designed our analysis to encompass a broad range of possible conditions. Specifically, we modeled three carbon demand scenarios and four carbon price levels.

Carbon Demand Scenarios:

[4] The number of landowners and the age of the forest were defined by overall inventory structure of a typical wood basked in the southeast US, and current share of the inventory being harvesting (around 3% according to the Forest Inventory and Analysis Database - USDA Forest Service, 2023).

[5] We selected the minimum and the maximum size based on conversation with forest managers in the region, and requirement for harvesting operability.

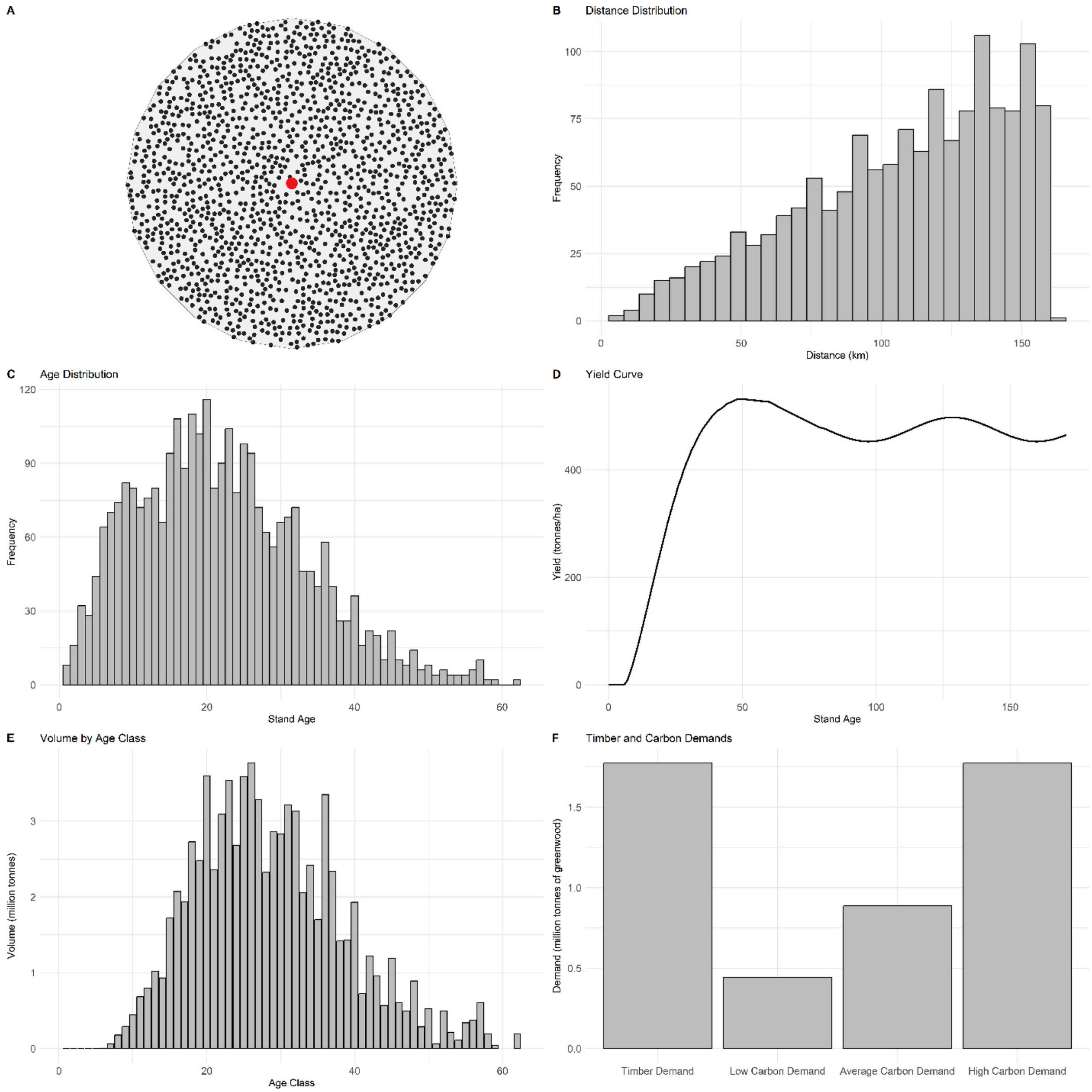

Fig. 1. (A) Spatial distribution of the mill and landowners, (B) Spatial distribution of landowners (C) Stand age Distribution, (D) Yield Curve, (E) Volume by Stand age, (F) Demand Scenarios.

(1) Low demand: 25% of current timber demand (≈452,000 t of green wood per year or 415,000 t of CO_2e per year)
(2) Average demand: 50% of current timber demand (≈905,000 t of green wood per year or 830,000 t of CO_2e per year)
(3) High demand: Equal to current timber demand (≈1.81 million tonnes of green wood per year or 1.66 million tonnes of CO_2e per year)

Carbon Price Levels:

(1) \$0.50/t CO2e, (2) \$5/t CO2e, (3) \$10/t CO2e, and (4) \$20/t CO2e.

4. Problem definition

The ABM model in this study runs simulations for 1000 iterations, with each iteration going across the study horizon spans 100 years (τ). The model starts with the original forest and market conditions including an expected stumpage price ($\langle P_{t=0} \rangle$), volume curve, V_a, where landowner i has been assigned their own age a. The volume is the product of forest area and volume per unit area (Fig. 2). The bidding process follows a sequential, cost-minimization approach rather than a competitive auction, meaning each landowner offers the lowest stumpage price they are willing to accept. These bids are calculated based on the Land Expectation Value (LEV) and then ranked by delivered cost, which determines selection by both the mill and the carbon aggregator.

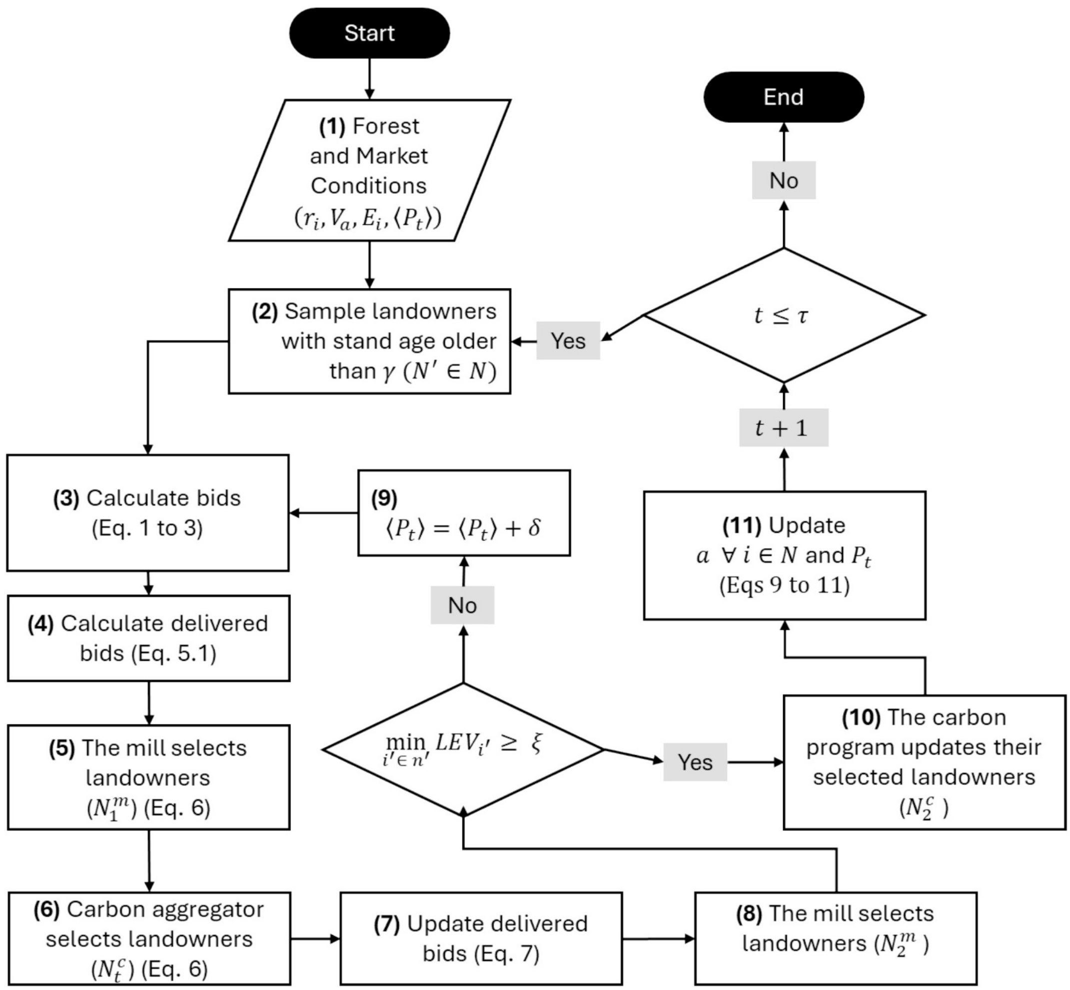

Fig. 2. Flowchart.

For each simulation, we follow ten steps:

(1) We randomly select an establishment cost (E_i) and discount rate (r_i) for each landowner from a uniform distribution between \$375/ha and \$750/ha, and 2% and 6%, respectively.
(2) A mill samples N' landowners from the total set N. N' is the random selection of 25% of landowners with forests older than the minimal clearcut age (γ; assumed to be 19 years – a common minimal in the Southern US).
(3) With the expected stumpage price, establishment costs, yield curve, and a discount rate, landowners in N' estimate their respective maximum Land Expectation Value ($maxLEV_{it}$) and calculate their bid b_{it} (Eqs. 1, 2, and 3), which is the minimum stumpage price the landowner is willing to accept in order to harvest.
(4) For the set N', we estimate d_{it} (Eq. 5), which is a landowner's bid plus harvest and transportation costs.
(5) The mill selects the landowners with the lowest d_{it}, forming the set N_1^m from N'.
(6) From the set N_1^m, the carbon aggregator initially selects landowners with the lowest delivered bids (d_{it}) to meet its carbon demand (N_1^c). This strategy prioritizes landowners most likely to harvest, thus having the highest risk of immediate carbon loss. By targeting these landowners, the aggregator aims to counteract the mill's cost-minimizing procurement behavior (Eq. 6). However, whether the aggregator and the mill compete for the same landowners depends on relative carbon and timber prices: at low carbon prices, overlap is minimal, but as carbon prices rise, competition intensifies, potentially increasing stumpage prices and influencing wood product competitiveness in broader markets.
(7) Delivered bids are then updated to d'_{it} (Eqs. 4 and 7), which includes the carbon prices C for landowners that were selected by the carbon aggregator.
(8) At this point, the process starts again but with d'_{it}. The mill selects landowners from N' with the lowest delivered bids (d'_{it}), updating the set of landowners selected from N_1^m to N_2^m. Notice that N_1^m could be equal to N_2^m if the mill offsets the carbon offer for every single landowner in N_1^m.
(9) Stumpage prices might be at the levels where landowners cannot achieve the minimum profit required to manage their forests. To prevent unprofitable transactions, we implement a price floor mechanism: if a landowner's bid results in a maximum Land Expectation Value (LEV) below the threshold ξ, the landowner adjusts their expected stumpage price upward by a re-offer increment δ (\$0.11 per tonne of timber) and returns to step (3). Our minimal threshold is conservative (\$988/ha) is conservative in comparison to the data available to the public; Cubbage et al. (2022) estimated that the land costs in the Southeastern US with average productivity was \$2500/ha.

This incremental adjustment reflects a conservative increase in timber price expectations, ensuring gradual convergence toward economically viable bids without destabilizing the market.

(10) The carbon aggregator updates their selection of landowners (from N_1^c to N_2^c), but now it selects the landowners from N' and not in N_2^m by sorting d'_{it}. Mathematically, $N_2^c \subseteq N' \backslash N_2^m$.
(11) All landowners update their stand age and price expectation (Eqs. 8 to 11).
(1) At the end of these steps, there are three types of landowners, the ones selected by the mill (N_2^m), the ones selected by the carbon aggregator (N_2^C), and the ones selected by neither ($N^{ns} = N \backslash (N_2^m \cup N_2^C)$).

4.1. Landowner bid process

We assume that landowner agents are profit maximizers and timber production is their only existing source of income in the absence of carbon payments. In even-aged forest management, the optimal rotation is the result of the maximization of the LEV (Faustmann, 1849). In our model, landowners maximize *LEV* for each simulation and period as in:

$$\mathrm{maxLEV_{it}} = \max_{a} \frac{\langle \mathrm{P_t} \rangle \mathrm{V_a e^{-r_i a}} \;\; - \mathrm{E_i}}{1 - \mathrm{e^{-r_i a}}} \tag{1}$$

where $\langle P_t \rangle$ is the stumpage price expectation, V_a is the volume of the forest at age a,r_i represents the discount rate, E_i is the establishment cost.

In Eq. 1, *maxLEV* represents the returns from a regime with periodic harvests at optimal rotation length a^* in perpetuity. Landowners use a^* as a reference to estimate the current forest value (Kanieski da Silva et al., 2024; Klemperer et al., 2023). For instance, if landowners harvest their forest at age a, and $a < a^*$ at time t, then landowners expect to be compensated for harvesting earlier than the optimal rotation. On the other hand, if the stand age $a \geq a^*$, then the compensation is determined by a one-year delay in harvesting (Henderson and Abt, 2016; Newman, 1988). We impose a limit on this dynamic since the opportunity cost of delaying harvesting is higher than the marginal gains (assuming static prices and costs); we assume therefore that landowners with a forest older than 50 years would accept a 10% discount on their bid to clearcut as soon as possible and replant their forest. The 50-year threshold was chosen arbitrarily, reflecting a point at which a pine plantation in the Southeastern United States would typically exhibit structural and compositional characteristics resembling a natural forest. Mathematically, we can define the bidding conditions following Henderson and Abt (2016):

$$b_{it} V_a + maxLEV_{it} = \frac{\langle P_t \rangle V_{(a_i + k_i)} + maxLEV_{it}}{1 + e^{r_i k_i}} \tag{2}$$

where b_{it} (\$/tons) is the minimal bid at the stump that landowner i would accept to harvest during simulation *sim* and period t, V_a is the forest volume at age a (tons/acre), $maxLEV_{it}$ is the maximum Land Expectation Value (\$/acre) of landowner i at the optimal age a^*, k_i has two definitions depending on the stand age a: (1) if $a < a^*$, k_i is the number of years that the forest of landowner i would take to reach the optimal rotation a, or (2) if $a \geq a^*, k_i$ is set to 1, indicating a one-year postponement of harvest. After a few algebraic changes on Eq. (2), the bidding expression simplifies to:

$$b_{it} = \frac{\left(\frac{\langle P_t \rangle V_{(a_i + k_i)} + maxLEV_{it}}{1 + e^{r_i k_i}} - maxLEV_{it} \right)}{V_a} \tag{3}$$

With respect to the carbon aggregator, if landowner i is selected for participation in the carbon program during period t, their bid is represented by:

$$b'_{it} = C + b_{it} \tag{4}$$

where C is the price offered by the carbon aggregator. This allows for the addition of non-timber income to the landowner's decision-making process.[6]

4.2. Landowner selection process – wood consuming mill

The mill and the carbon aggregator have the same strategy when selecting landowners for either harvesting or delaying harvesting, respectively. Both sort landowners by their delivered bid (Eq. 5) subject to a specified demand for either timber, for the mill, or a minimal carbon deferral quantity, for the carbon aggregator (Eqs. 6, 6.1 and 6.2).

With H as the harvesting costs, T_i as the transportation costs from landowner i to the mill, and other parameters are described by Eqs. 3 and 4, delivered bids are then defined as:

$$d_{it} = b_{it} + H + T_i \tag{5}$$

and define:

$$D'_t = \{d_{1t}, d_{2t}, \ldots, d_{|N'|t}\}, \text{the set of delivered bids the size of set } N' \tag{5.1}$$

where N is the maximum number of landowners.

The selection of the landowners or carbon aggregator by the mill is based on the following: Assume the set of demand agent types is represented by Ψ; within this set we have m for mill and c for carbon aggregator. We define W_o^Ψ to be the volume of product demanded by agent Ψ and supplied by the o-th lowest value of d_{it} . We assume the demand agent selects the smallest set of landowners, N_t^Ψ, that exceeds the target demand W^Ψ, starting from the lowest delivered bid by landowners. In other words, they solve:

$$min|N_t^\Psi| \tag{6}$$

$$\text{s.t.} \sum_{o=1}^{|N_t^\Psi|} W_o^\Psi (D') \geq W^\Psi \tag{6.1}$$

4.3. Landowner selection process – carbon program

The carbon program selects landowners who appear on the wood-consuming mill's procurement list (step 6, Fig. 2). In steps (8) and (10), the program incorporates the carbon price C into the landowner's bid (b'_{ist}) when calculating delivered prices. The optimization problem defined by Eqs. (6) and (6.1) is solved three times during steps (6), (8), and (10). The key distinction among these steps is whether the carbon price is included. In step (6), bids consist solely of timber values (Eq. 5), whereas in steps (7) and (9), the carbon price is added to the delivered bids (Eq. 7).

$$d'_{it} = \begin{cases} b'_{it} + H + T_i & \forall i \in N_t^c \\ d_{it} & otherwise \end{cases} \tag{7}$$

where the delivered prices are updated if the landowner i is in the set of landowners selected by the carbon aggregator (N_t^c). Notice that $d'_{it} = d_{it}$ if the landowner i is not selected by the carbon aggregator.

4.4. Forest inventory and harvesting transitions

The transition between stand ages (a) across period t are represented as:

[6] Following Hartmann (1976), the implicit assumption is that pricing non-timber benefits will extend rotation age.

$$x_{iat} = \begin{cases} \mu_{ia} \\ h_{ia^{*}t-1} \\ x_{ia-1t-1} - h_{ia-1t-1} \\ x_{iat-1} - h_{iat-1} + (x_{iat-1} - h_{ia-1t-1}) \end{cases}$$

t = 0

t > 0 and a = 0

if t > 0 and 0 < a < A

if t > 0 and a = A (8)

where μ_{ia} is the initial area of landowner i at stand age a, x_{iat} and h_{iat} are respectively the area inventory and area harvested of landowner i, age a, and period t. a^{*} in $h_{ia^{*}t-1}$ is the age in which the stand i is completely clearcut.

The first term of Eq. (8) ensures the initial condition for area of timber is always the same across every landowner, stand age, and simulation. Term two enforces that every area harvested is replanted; terms three and four ensure that the area inventory is updated as the harvest decision occurs. Notice that in term four, the forest area accumulates over the oldest stand age.

The volume harvested and volume inventory are then defined in Eq. 9.1 and Eq. 9.2 respectively.

$$Q_t = \sum_{i}^{N'} V_a \times h_{iat} \tag{9.1}$$

$$I_t = \sum_{i}^{N'} V_a \times x_{iat} \tag{9.2}$$

4.5. Stumpage price and price expectation

An adaptive feature of our agent-based model is that landowners update their stumpage price expectation from one period to the next. Henderson and Abt (2016) used the market clearing bid as the new expected price. We use an alternative formulation based on how timber price data are typically collected and averaged – that is, transaction level data are volume weighted averaged, and this average is reported to the public. The stumpage price that emerges in a given simulation and year, a weighted average of bids, is therefore:

$$P_t = \frac{\sum b_{it} \times q_{it}}{Q_t} \tag{10}$$

All landowner agents can observe this reported market price, and it therefore provides an anchor for expectations. We go one step beyond this and imbue landowner agents with a simple forecasting ability, such that landowners' price expectation is inversely proportional to indexed change of forest inventory volume. This assumption is consistent with empirical timber supply specifications, which show that increasing inventory volume is correlated with lower prices (Yin and Newman, 1997; Henderson et al., 2020). So the price expectation is a function of the lagged stumpage price and the ratio of lagged forest volume terms. These calculations are represented by Eq. 11,

$$\langle P_t \rangle = P_{t-1}\left(\frac{I_t}{I_{t-1}}\right) \tag{11}$$

4.6. Carbon program costs

To estimate the cost of the carbon program relative to additional carbon sequestration, we define:

$$CPC = \frac{\sum_{t=0}^{T} \left(C \times W_t^C\right) \Big/ (1+r)^t}{Q_T' - Q_T} \tag{12}$$

where C is the carbon prices, r is the discount rate, W_t^c are the quantity demanded of carbon, Q_T and Q_T' are the quantity of carbon sequestrated of carbon in scenarios without carbon program and with carbon programs respectively.

This formulation discounts annual carbon payments over the simulation horizon and divides by the net additional carbon achieved, providing a cost per tonne of additional carbon.

4.7. Mill costs

Similarly, the mill's additional cost due to the carbon program is calculated as:

$$MC = \frac{\sum_{i=0}^{I} \sum_{t=0}^{T} \frac{(d_{it}' \times q_{it}') - (d_{it} \times q_{it})}{(1+r)^t}}{Q_T' - Q_T}$$

where d_{it}' and d_{it} is the delivered prices under the scenario of carbon programs and no carbon program respectively. Likewise, q_{it}' and q_{it} are the total timber supplied.

This equation captures the discounted difference in procurement costs between scenarios, normalized by additional carbon sequestration.

5. Results

The interplay of biological growth, landowner objectives, forest inventory, and timber demand links all variables over time through dynamic responses of the agents described earlier to varying demand and price signals introduced by the carbon aggregator. In our model, the mill minimizes procurement costs by selecting landowners offering the lowest delivered bids, while the carbon program targets landowners most likely to harvest, creating direct competition for the same stands.

Our results show how the multiple scenarios of carbon prices and demand impact: (1) stand age structure, (2) distance to the mill, (3) stumpage prices and delivered prices, and (3) carbon stock, emission and costs. In results (1) and (2) we disaggregated the landowners into three categories: (i) "Not selected" refers to landowners excluded from both mill and carbon programs. (ii) "Timber market" indicates landowners chosen by the mill, while (iii) "Carbon market" refers to those selected by the carbon program.

5.1. Stand age structure

The presence of the carbon program significantly altered the stand age structure, reflecting one of the key leakage effects. Over the simulation horizon (Fig. 3), two consistent patterns emerged across all scenarios involving a carbon aggregator: (1) the average stand age of the landowners was almost always greater than the optimal financial rotation age (dashed straight line) and (2) landowners enrolled in the carbon market generally manage older forests compared to those supplying the timber market. The only exception occurs under scenarios combining low carbon demand with a carbon price of \$10/t CO2e, and average carbon demand at the same price, where the age classes of landowners selected by the carbon program closely resemble those chosen by the mill (Table 1 and Fig. 3).

Our results also indicate that the fluctuation in the average stand ages of landowners selected by the mill (Timber Market) was similar across scenarios. All the statistics (mean, median, standard deviation (SD), maximum and minimum) were very similar; the average age for each scenario, for instance, was between 37 and 38 years old, and the standard deviation between 20 and 22 years old (Table 1).While the

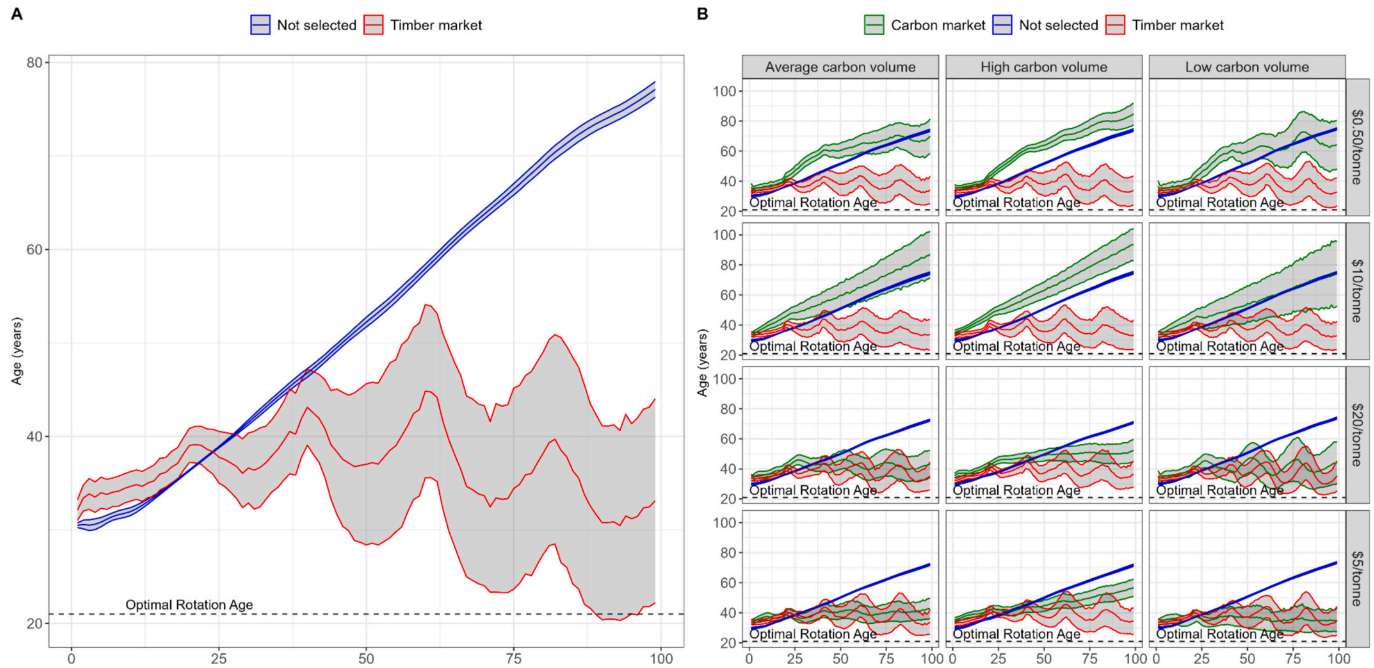

Fig. 3. (A) Average stand age (years) of landowners' forest with no carbon aggregator. (B) Average stand age in scenarios with a carbon aggregator. The horizontal axis represents the period (t, years). Not selected" refers to landowners excluded from both mill and carbon programs. "Timber market" indicates landowners chosen by the mill, while "Carbon market" refers to those selected by the carbon program.

Table 1
The stand age summary statistics of landowners participating in the carbon market varies with carbon price and demand.

Scenario	Carbon Market					Not Selected					Timber Market				
	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min
BAU						54	49	39	155	0	38	28	22	140	19
$0.50/t CO2e Low carbon demand	56	49	28	141	20	53	47	38	155	0	38	29	21	141	19
$0.50/t CO2e Average carbon demand	58	51	28	147	20	53	46	38	155	0	38	29	22	141	19
$0.50/t CO2e High carbon demand	63	59	30	147	20	53	46	38	155	0	38	29	22	147	19
$5/t CO2e Low carbon demand	41	33	22	141	20	53	45	38	155	0	38	30	21	141	19
$5/t CO2e Average carbon demand	42	35	21	147	19	52	45	37	155	0	38	31	20	147	19
$5/t CO2e High carbon demand	47	40	24	153	19	52	45	36	155	0	39	32	20	153	19
$10/t CO2e Low carbon demand	36	31	16	162	20	52	45	37	167	0	38	30	21	168	19
$10/t CO2e Average carbon demand	39	35	18	169	19	52	45	37	168	0	38	31	20	168	19
$10/t CO2e High carbon demand	46	40	22	158	19	52	46	36	158	0	39	32	20	152	19
$20/t CO2e Low carbon demand	54	44	30	148	20	53	46	38	155	0	38	29	21	148	19
$20/t CO2e Average carbon demand	60	54	31	148	20	53	46	38	155	0	38	30	21	148	19
$20/t CO2e High carbon demand	65	60	31	148	20	53	47	37	155	0	38	30	21	148	19

stand age variation and average increased from ~30 years old until ~40 years old at the start of the simulation, it declined in to the direction of the optimal age after 20 years into the simulation.

For landowners engaged in the carbon market, fluctuations in demand and carbon prices resulted in varying stand ages. At a carbon price of $0.50/t CO2e (first row in Fig. 3B), stand ages increased significantly over the first 30 years, then stabilized under low and average demand for carbon (first and second columns in Fig. 3B). However, a positive trend was observed with high carbon demand at the lowest carbon price (third column in Fig. 3B). The overall average stand age increased with carbon volume at a carbon price of $0.50/ton, from 56 years in low carbon demand scenarios to 63 years (Table 1 – Rows 2 to 4). At higher carbon prices of $5/t CO2e and $10/t CO2e (second and third rows in Fig. 3B), the results differed substantially. In these scenarios, the average stand age of landowners selected by the carbon aggregator were similar to those in the timber market. Under low carbon demand, the average stand age in the carbon market were 41 and 36 years for the $5/t CO2e and $10/t CO2e scenarios, respectively. For high carbon demand, these averages increased to 47 ($5/t CO2e) and 46 years ($10/t CO2e). The dynamic paths over time were also similar, with more fluctuation under low carbon demand and a positive trend under high carbon demand.

Notably, with higher carbon price ($20/t CO2e), the average age increased in every scenario of carbon demand. For instance, in low carbon demand in both carbon prices the average age was 54 years old, lower than the same demand and carbon prices of $0.50. This was due to the fact that, at higher prices, the mills elect to procure timber resources from alternative landowner agents as price competition from the carbon aggregator increases. This trend affects other variables like distance and stumpage and delivered prices.

5.2. Distance to the mill

Another important leakage effect was the increased distance mills needed to travel to procure wood fiber. In the baseline scenario without a carbon aggregator (BAU), mills sourced timber from landowners located relatively close to the mill. By contrast, when the carbon program was introduced, procurement distances expanded, as mills had to seek alternative suppliers after losing nearby landowners to carbon contracts (Fig. 4A).

Across all scenarios where the carbon program is present, the average distance to the mill for participants in the timber market oscillates during the simulation period, varying from around 48 km to 80 km in the first 10 years, and stabilizing between 73 and 112 km after the simulation reaches approximately 20 years. Although, the landowner that are selected by the mill appear to have no effect on the average distance across the carbon scenarios and landowner types, there is an increase in the minimal (and maximal) distance to the mill for landowners participating in the timber market, from 30 km at the $0.50/t CO2e (low carbon demand) to 39 km at the $10/t CO2e (low carbon demand) (Table 2). In the extreme case, the difference between the lowest carbon prices with low demand (30 km), and $10/t CO2e with high demand for carbon (54 km) is approximately 24 km. Thus, the mill does have to seek out landowners further from the mill site to procure fiber, and landowners closer to the mill are not selected in the procurement decision when the delivered prices rise, relative to landowners further away, due to the additional carbon price component.

The distance between mills and landowners in the carbon market is more responsive to changes in carbon prices than to scenarios for carbon demand (Fig. 4B). As carbon prices increase, landowners selected by the aggregator tend to be located closer to the mill. For example, in the low carbon demand scenario, the average distance of landowners in the carbon program is 130 km at $0.50/t CO2e, whereas it decreases to 30 km at $20/t CO2e (Table 2). This increased proximity intensifies competition between the mill and the aggregator, thereby driving up prices, as discussed next.

5.3. Stumpage prices and delivered prices

Given the observed changes in stand age classes and procurement distances, stumpage and delivered prices were also affected, representing another dimension of leakage. The introduction of a carbon aggregator that competes with a wood-consuming mill for forest landowners increases stumpage prices in all modeled scenarios, except when prices reach $20/t CO2e (Fig. 5).

The combined effect of the carbon program's size and its willingness to pay for harvest deferrals strongly influenced timber price dynamics. At the stump, timber prices were minimally affected when carbon prices were set at $0.50/t CO_2e. For example, the average difference between scenarios without carbon and those paying $0.50/t CO_2e was only $0.36/t ($13.62/t versus $13.99/t) under low carbon demand and $0.56/t ($13.62 versus $14.18) under high carbon demand. In contrast, carbon prices of $5/t CO_2e and $10/t CO_2e significantly altered timber price patterns. Under high carbon demand, stumpage prices rose from approximately $15.43/t in year 1 to $22.05/t and $25.35/t by the end of the simulation for the $5 and $10 scenarios, respectively. At $5/t CO_2e, price increases were moderate during the first 25 years for low and average carbon demand (around $22/t), followed by substantial growth thereafter. At a carbon price of $10/t CO_2e, stumpage prices under

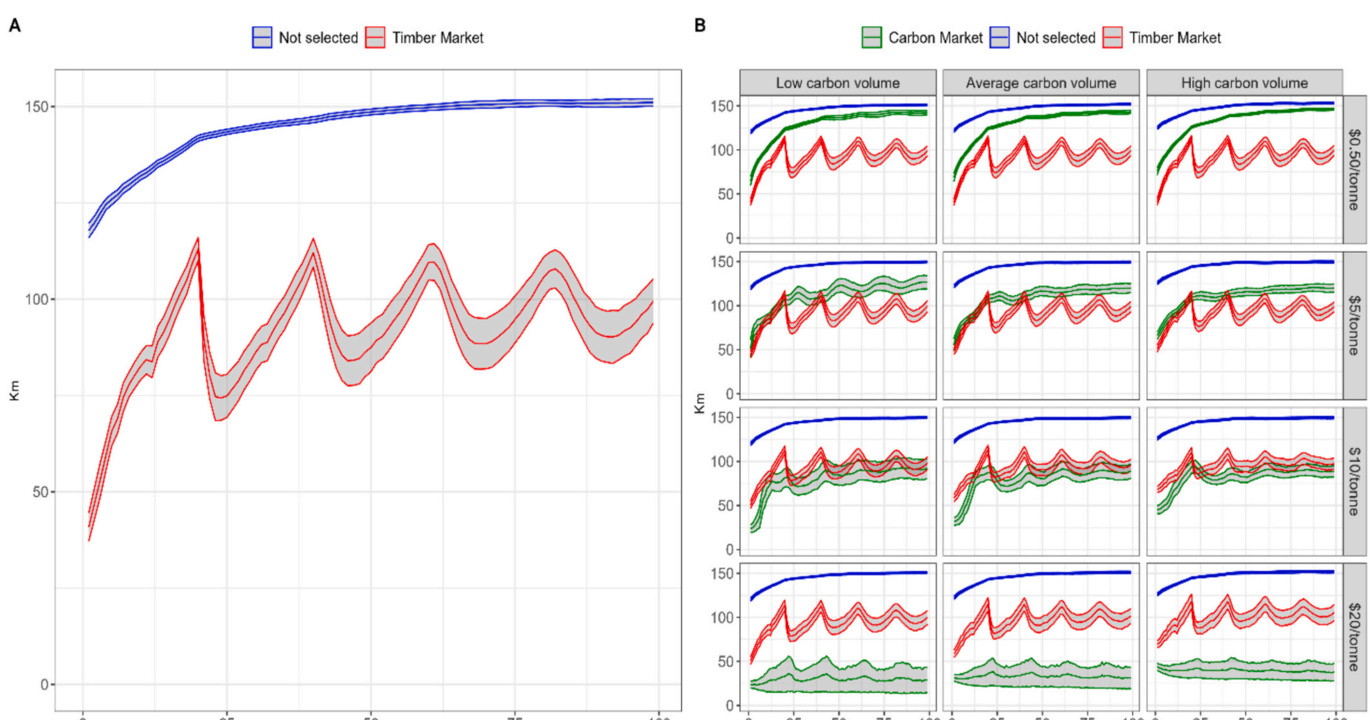

Fig. 4. (A) Average distance in kilometer in the scenario without carbon. (B) Average distance in kilometer in the scenarios with carbon. The horizontal axis represents the period (t, years). Not selected" refers to landowners excluded from both mill and carbon programs. "Timber market" indicates landowners chosen by the mill, while "Carbon market" refers to those selected by the carbon program.

Table 2
The distance in km from the mill and landowners across all scenarios.

Scenario	Carbon					Not Selected					Timber Market				
	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min	Mean	Median	SD	Max	Min
BAU	–	–	–	–	–	145	145	8	153	112	91	92	13	125	28
$0.50/t CO2e Low carbon demand	130	130	17	150	50	146	146	7	153	113	91	91	13	127	30
$0.50/t CO2e Average carbon demand	130	131	17	149	50	146	146	7	154	115	91	91	13	124	31
$0.50/t CO2e High carbon demand	133	133	17	148	61	148	148	7	156	118	91	91	13	127	31
$5/t CO2e Low carbon demand	112	111	15	147	21	145	145	7	152	113	91	91	13	128	35
$5/t CO2e Average carbon demand	109	109	14	140	32	145	145	7	152	116	91	91	12	125	38
$5/t CO2e High carbon demand	111	111	12	137	50	146	146	6	153	119	92	92	12	127	40
$10/t CO2e Low carbon demand	80	80	16	145	13	145	145	7	153	113	92	92	12	126	39
$10/t CO2e Average carbon demand	80	80	14	127	21	145	145	6	153	115	93	93	10	130	41
$10/t CO2e High carbon demand	83	82	11	122	32	146	146	6	153	119	95	95	8	126	54
$20/t CO2e Low carbon demand	30	25	3	118	9	145	145	7	153	114	94	94	12	132	38
$20/t CO2e Average carbon demand	33	30	2	104	12	146	146	7	154	115	96	96	11	132	43
$20/t CO2e High carbon demand	40	37	1	93	21	147	147	6	155	1119	100	101	10	137	55

average and high carbon demand rose sharply during the first 20 years, increasing from $13.70/t to $17.25/t for average demand and to $22.53/t for high demand. In contrast, prices under low carbon demand remained relatively stable at around $16.53/t. Finally, scenarios with carbon prices of $20/t CO_2e exhibited stable stumpage prices, closely resembling those observed in the absence of a carbon program, with average stumpage prices of $13.83/t, $13.81/t, and $13.82/t for low, average, and high carbon demand, respectively (compared to $13.62/t in the no-carbon scenario).

In Fig. 6, delivered price fluctuations were noticeably lower than those observed for stumpage prices. During the first 25 years, delivered prices increased across all scenarios before stabilizing at an average of approximately $40.78/t in the baseline scenario without a carbon program. Under the $0.50/t CO2e scenario, delivered prices remained virtually identical to the baseline, reflecting minimal influence from the carbon aggregator. As noted in the distance and stand age analysis, landowners selected by mills differed from those chosen by the carbon aggregator at this price level, with carbon program participants generally located farther from the mill. This spatial distribution slowed the rate of price increases under both the $5/t CO2e and $10/t CO2e scenarios.

Peak delivered prices during the first 25 years reached $50.15/t and $54.55/t for carbon prices of $5/t CO2e and $10/t CO2e, respectively. Variability in carbon demand had a smaller effect on delivered prices compared to stumpage prices. Moreover, average delivered prices across scenarios generally fell within each other's standard deviation, indicating smoother transitions relative to stumpage price changes. For example, under the $5/t CO2e scenario, average delivered prices and standard deviations were $21.05/t and $1.14/t at high carbon demand, compared to $16.64/t and $0.96/t at low carbon demand. Overall, the smoother price transitions indicate that carbon programs, while influencing procurement dynamics, do not destabilize delivered price trends to the same extent as stumpage prices.

5.4. Carbon stock and emission

This subsection examines the impact of increased carbon demand on total forest carbon stock, transportation emissions, and associated costs. While carbon demand is met in every scenario, their sequestration and emission dynamic varies across the scenarios. Fig. 7 illustrates these effects, detailing (A) Net carbon stock relative to the baseline mean by scenario over 100 years (tonne CO2e), (B) Accumulated net carbon emissions from transportation relative to the baseline (tonne CO2e), and (C) Net carbon sequestration (A) minus (B).

Analysis of carbon stock and transportation-related emissions demonstrates that the one-year harvest deferral protocol delivers measurable additionality and contributes to a form of carbon permanence (i.e., increased aggregate net carbon stock over the study horizon). Across all scenarios, carbon stocks at the landscape level remain consistently higher than the baseline (BAU), indicating that additional carbon is sequestered. Moreover, this positive difference grows over time, suggesting a dynamic that supports long-term retention of carbon and a degree of permanence.

Fig. 7 shows that higher carbon prices and demand levels generally lead to greater forest carbon sequestration but also increase transportation emissions due to changes in procurement patterns. At high carbon prices, such as $20/t CO_2e, this dynamic changes: mills become less competitive with carbon programs and respond by sourcing timber from more distant landowners, which raises transportation costs and emissions. This behavior has two critical implications. First, the total carbon sequestered after 100 years is significantly lower than in scenarios with moderate carbon prices. For example, under high demand, the cumulative sequestration was 3.0 and 2.9 million tonnes of CO_2e for the $5 and $10/t CO_2e scenarios, respectively, but only 1.2 million tonnes for the $20/t CO_2e scenario. Second, the cost of securing this carbon becomes prohibitively high at elevated prices, as payments increase without proportional gains in long-term sequestration. In other words, while higher carbon prices improve short-term additionality, they introduce inefficiencies and unintended consequences over time, suggesting that moderate carbon prices ($5–$10/t CO_2e) offer a better balance between ecological benefits and economic viability.

5.5. Carbon costs

We present the costs of the carbon program in two ways: (1) Carbon program cost (Table 3) and (2) Mill cost (Table 4). For the carbon program, the cost of sequestered carbon is higher than the initial value paid across all scenarios and discount rates. This demonstrates that the

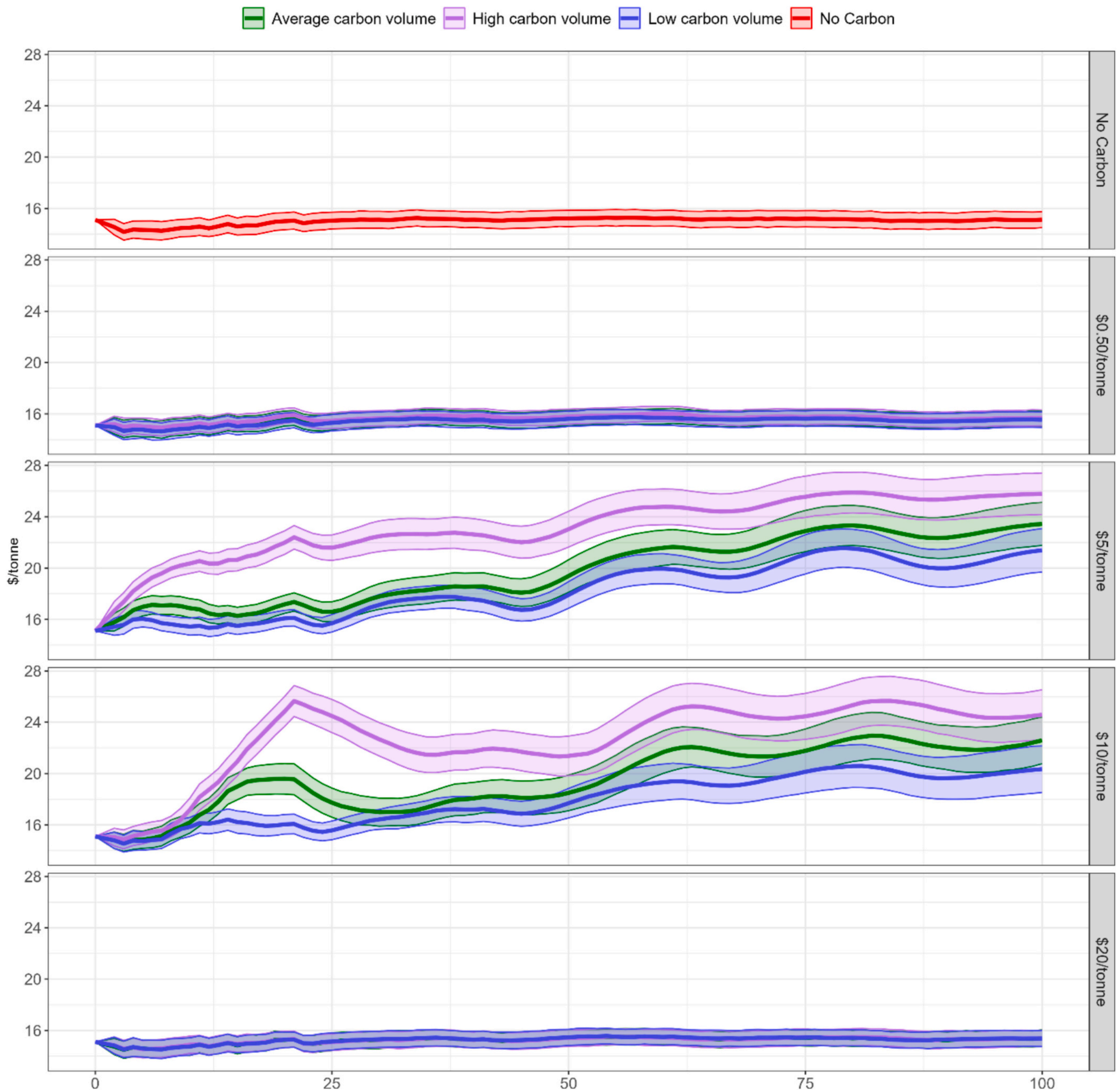

Fig. 5. Stumpage Prices ($/tonne CO2e) for scenarios of no carbon market, low carbon volume, average carbon volume and high carbon volume by carbon prices of $0.50/t CO2e, $5.00/t CO2e, $10.00/t CO2e, and $20.00/t CO2e. The horizontal axis represents the period (t, years).

carbon sequestered by participating landowners does not fully offset the program's costs when evaluated against the total amount sequestered over 100 years. From the mill's perspective, a carbon program paying $0.50/t of CO2e has a negligible financial impact, allowing them to remain competitive. Their competitiveness is reduced, however, when carbon prices rise to $5/t and $10/t of CO2e. The $20/t CO2e price point presents mixed results. In a low-demand scenario, mill operations would not be financially affected, and the procurement team would likely still find affordable suppliers. In contrast, as carbon demand increases, affordability depends on a higher discount rate (specifically 6% in our case) to justify the costs.

Last, and perhaps most important, the discounted cost per unit ($/tonne CO2e), or the program price, in Table 3 reveals the price equivalent of additional carbon over 100 years under alternative discount rates – in effect a carbon permanence price. Depending on factors such as risks to forests, future alternative income streams (i.e., timber harvests), continued availability of carbon credits, discount rates, and landowner preferences, it is unknown if the carbon in the program is maintained or released after the study horizon. For instance, when all discounted costs at a 0% rate exceed the program's nominal price, it indicates that the total payments made for carbon storage are higher than the value of the additional carbon retained after 100 years. In other words, if the program paid for one tonne of carbon today but that tonne is not still sequestered at the end of the simulation horizon, the effective cost per tonne rises above the initial program price. This discrepancy signals that the carbon was only temporarily stored—reflecting limited permanence—because the one-year deferral does not guarantee retention over the full 100-year period.

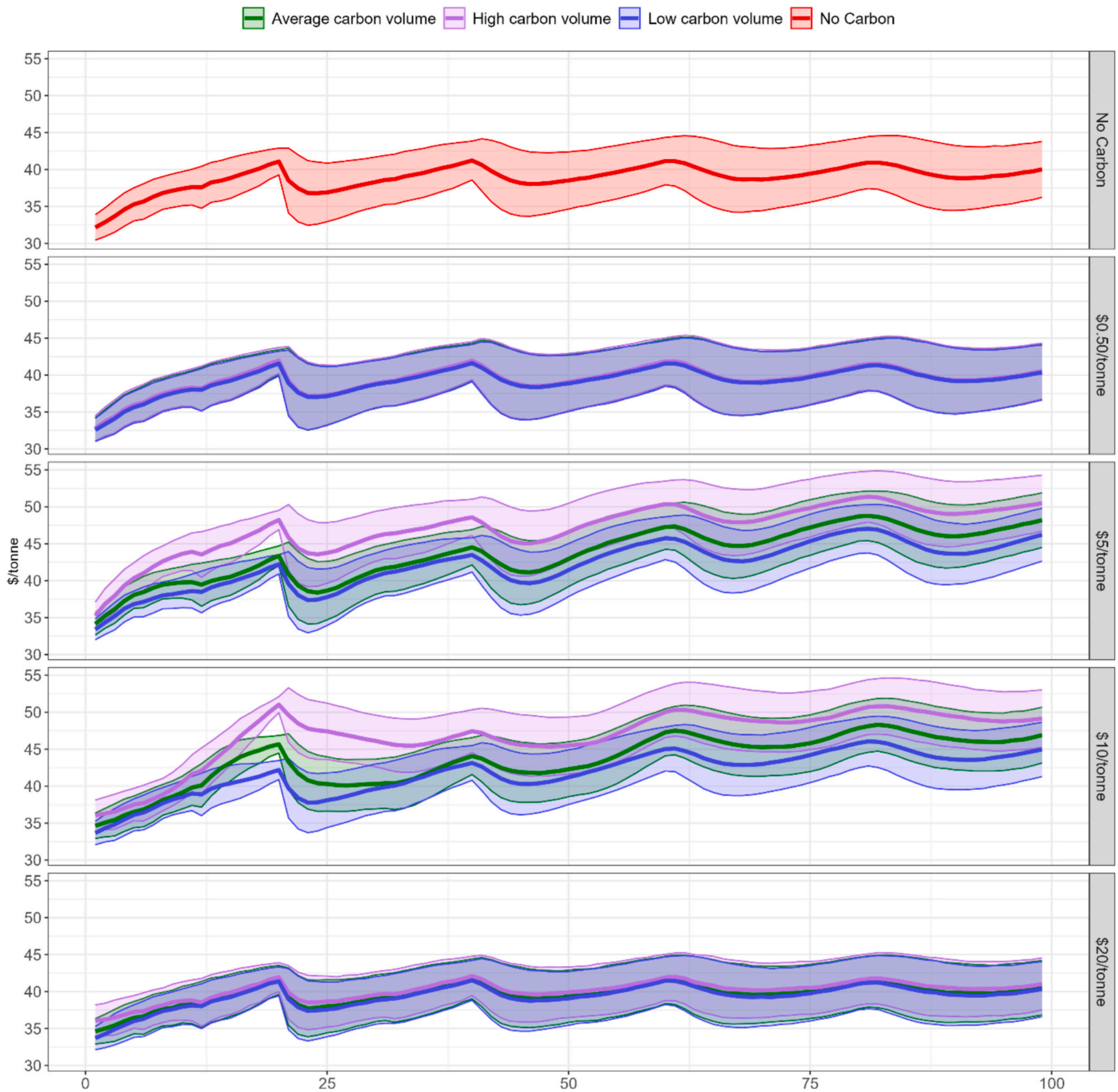

Fig. 6. Delivered Prices ($/tonne CO2e) for scenarios of no carbon market, low carbon volume, average carbon volume and high carbon volume by carbon prices of $0.50/t CO2e, $5.00/t CO2e, $10.00/t CO2e, and $20.00/t CO2e. The horizontal axis represents the period (t, years).

This outcome is expected, because the one-year deferral places only a temporary hold on harvests. If all the carbon paid for by the program remained sequestered for the full 100-year horizon, then the effective cost per tonne of additional carbon would simply equal the program's nominal price. From the perspective of a market designer, the lowest cost per unit represents the most effective carbon program, so the $5 and $10 programs at high demand achieve the best carbon additionality outcomes at the lowest price. To compare these one-year harvest deferral programs to alternative carbon abatement programs, particularly those with high upfront costs, it is necessary to choose a discount rate.

6. Discussion and conclusions

In this study, we examine how the introduction of a forest carbon aggregator, offering one-year harvest deferral contracts has potential for carbon additionality and permanence, with leakage effects manifesting as changes in stand age structure, procurement distance and ultimately on timber prices. We developed a spatial agent-based model that simulates landowners with diverse forest structures and financial objectives, allowing them to choose between deferring harvest for one year under a carbon contract or selling timber, if selected, to the mill. Their decisions follow a Faustmann-based optimization approach, balancing the trade-off between immediate timber revenue and carbon payments, by delaying harvest for an additional year, with the ability to remain in the program for the duration of the simulation, given the combination of all

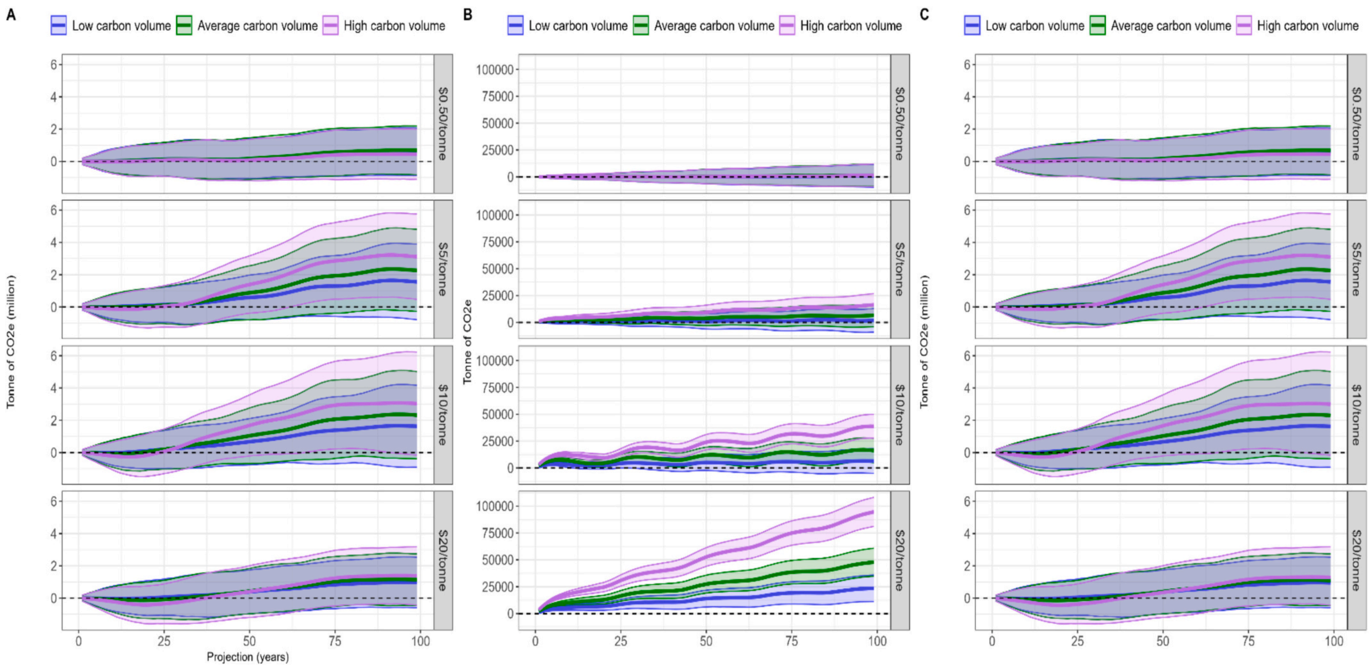

Fig. 7. (A) Net carbon stock relative to the baseline mean by scenario over 100 years (tonne CO2e), (B) Accumulated net carbon emissions from transportation relative to the baseline (tonne CO2e), (C) Net carbon sequestration (A) minus (B). The horizontal axis represents the period (t, years).

agents' actions.

Our findings apply specifically to fast-growing forest plantations with an age-class distribution typical of the Southeastern United States. The leakage analysis shows that harvest deferrals modified the age class structure as well as the spatial distribution of timber suppliers (landowners), driving up stumpage prices and expanding the mill's procurement radius to secure sufficient wood fiber. However, the effect on forest structure is more complex. By delaying harvest one additional year, **biological growth increases**, leading to a **higher share of older forests in the basin**, which enhances carbon sequestration but also alters the timber market's long-term equilibrium. In the scenarios with weak competition between the mill and carbon aggregator ($0.5/ t CO2e and $20/t CO2e), due to these deferred harvests, over time, fewer landowners (with increasing volumes per acre) are required to satisfy the carbon aggregator's goal, leading to a divergence among landowner agents—with those participating in the carbon market, typically holding their forest longer than those who neither enrolled in the program nor harvested their forest for mill consumption.[7]

At a carbon price of $10/t CO2e, the system reaches a tipping point where competition between the mill and the carbon aggregator intensifies. At this threshold, variations in delivered bids lead to more cases where both agents target the same landowners. This price level also forces mills to procure timber from greater average distances than the carbon aggregator. Overall, carbon programs at this tipping point enhance sequestration beyond the baseline but introduce trade-offs, notably higher stumpage and delivered prices. This tipping point can be interpreted as the carbon price crossing a large share of landowners' implicit break-even values for one-year harvest deferral, consistent with thresholds in analytical deferred-rotation models and with stand-level reservation prices estimated for annual harvest postponement (Tanger et al., 2022; Sartori et al., 2024).

Our modeling does not allow for the possibility of mill closure. Multiple pulp mills closed their operation in the Southeast US, including one in Texas (International Paper, 2023), two in Florida (WestRock, 2022; Georgia-Pacific, 2023), and one in South Carolina (International Paper, 2024). Limited timber market opportunities could lead some landowners to newly participate in carbon offset programs as an alternative source of income. As more forestland is enrolled under the carbon programs, investors may be more hesitant to locate new mills in those basins with present aggregators, ceteris paribus. This adaptation by mills could further complicate the situation as the expected additionality from carbon offsets may face greater scrutiny when there is a declining probability of harvest due to reduced mill activity. Further, while our model shows an advantageous price increase for landowners resulting from the presence of a carbon aggregator, the additional increase in delivered prices may induce existing mills to reduce capacity or shift capacity to other basins and possiblyshutter operations, jeopardizing the primary source of income for landowners. Any of those outcomes would amount to a form of reverse leakage, where due to the presence of the carbon program, the mill would seek to reduce procurement in the existing basin and paradoxically undermine additionality targets for the carbon program– since absent a demand source, forests are under less pressure to harvest. Our current model does not capture scenarios where the wood mill could strategically alter its demand or exercise market power in response to carbon program competition. Incorporating such adaptive behavior, such as reducing procurement, adjusting bid strategies, or leveraging spatial advantages, represents a logical next step for evaluating these programs at the wood basin scale.

We find evidence of additionality from the one-year deferral protocol, across all scenarios, with only the high demand for carbon and price conditions leading to a short term (first 25 years) reduction in carbon on the landscape. Less clear is permanence. With most projects, permanence is only guaranteed for the life of the contract (in some cases as low as 40 years, in others upwards of 100 to 150 years are common). Even across a landscape level, the only permanent carbon is the amount still additional in the final year of the simulation. From our perspective this appears, at a landscape level to provide a sort of "rolling" permanence, where the carbon contract moves from one landowner to another across the basin over time, consistent with Marland et al.'s (2001) argument

[7] The age classes of landowners selected by the carbon program become shift older than the landowners selected by the mill and the landowners that are not selected by either (Figure 3b) at lower prices for the entire simulation and initially (through ages 50 to 75 years), at higher prices and then giving way to those who are not enrolled with the aggregator or selected by the mill.

Table 3
Total carbon sequestrated by timber management relative to the baseline.

Scenario	Net carbon sequestration thousand tonne of CO2e)*.	Carbon Price ($/tonne CO2e)*	Carbon Price ($/ tonne CO2e)*	Carbon Price ($/tonne CO2e)*
		Discount Rate		
		0%	3%	6%
$0.50/tonne CO2e Low carbon demand	598	41	13	7
$0.50/tonne CO2e Average carbon demand	683	69	22	12
$0.50/tonne CO2e High carbon demand	442	209	67	35
$5/tonne CO2e Low carbon demand	1,557	157	50	26
$5/tonne CO2e Average carbon demand	2,262	208	66	35
$5/tonne CO2e High carbon demand	3,099	298	95	50
$10/tonne CO2e Low carbon demand	1,624	300	96	50
$10/tonne CO2e Average carbon demand	2,298	409	130	69
$10/tonne CO2e High carbon demand	2,991	617	197	104
$20/tonne CO2e Low carbon demand	948	1,018	325	172
$20/tonne CO2e Average carbon demand	1,093	1,712	546	288
$20/tonne CO2e High carbon demand	1,279	2,879	918	483

Note: *The total cost and cost per unit were discounted through the one hundred years in the simulation.

that temporary projects can yield results that equivalent to permanent sequestration through scale and with subsequent work examining the time value of temporary carbon storage (Parisa et al., 2022, Galik et al., 2022). It is important to note, however, that these increased carbon storage benefits are partly contingent on continued demand from carbon aggregators (Kirschbaum, 2006). In the average and high carbon demand scenarios with a carbon price of $10/t CO2e, assuming a 6% discount rate, we find that the long-term carbon cost per unit is in equilibrium with the price paid by the aggregator; in other words, the additional cost is less than or equal to $10/t CO2e, indicating that collectively, landowners, carbon aggregator and mill, still have positive financial returns.

Although we utilized a simulation-based approach, our parameters attempted to mimic real world wood basins using empirical forest

Table 4
Total carbon sequestrated by timber management relative to the baseline and their relative costs.

Scenario	Net carbon sequestration (thousand tonne of CO2e)*	Total Additional Cost faced by the mill ($ thousands)*			Cost per unit ($/tonne CO2e)*		
		Discount Rate			Discount Rate		
		0%	3%	6%	0%	3%	6%
$0.50/tonne CO2e Low carbon demand	598	769	41	2	1.29	0.07	0.00
$0.50/tonne CO2e Average carbon demand	683	1,058	57	3	1.55	0.08	0.00
$0.50/tonne CO2e High carbon demand	442	1,170	63	4	2.65	0.14	0.01
$5/tonne CO2e Low carbon demand	1,557	10,890	584	34	6.99	374	21.85
$5/tonne CO2e Average carbon demand	2,262	14,390	771	45	6.36	340	19.88
$5/tonne CO2e High carbon demand	3,099	18,538	994	58	5.98	320	18.69
$10/tonne CO2e Low carbon demand	1,624	8,753	469	27	5.39	288	16.84
$10/tonne CO2e Average carbon demand	2,298	12,143	651	38	5.28	283	16.51
$10/tonne CO2e High carbon demand	2,991	15,961	855	50	5.33	286	16.67
$20/tonne CO2e Low carbon demand	948	590	32	2	0.62	0.03	0,00
$20/tonne CO2e Average carbon demand	1,093	956	51	3	874	46	2.73
$20/tonne CO2e High carbon demand	1,279	1,911	102	6	1.49	80	4.67

Note: *The total cost and cost per unit were discounted through the one hundred years in the simulation.

inventory analysis data, when possible. Our results did not contradict the other basin level study by Rossi et al. (2023), which also utilized FIA data to characterize actual wood basins. Like our study, they found that carbon programs could be costly, particularly in pulpwood markets due to the increase in prices relative to sawlogs. The projection of the forest inventory in their study showed more variation over time, but smaller differences across the scenarios analyzed. Strict comparisons with Rossi et al. (2023) are difficult since, among other reasons, their model contains aggregate supply curves rather than individual harvest decisions, and it also simulates increases in forest productivity over time due to carbon fertilization (Henderson et al., 2020).

The ABM approach means that while our analyses are tailored to reflect key features of plantation forestry in the Southeastern US, the general approach of modeling landowner or land manager harvesting behavior in response to changes in timber and carbon markets has the potential to give insights into the additionality of carbon markets across a range of forestry systems. However, we recognize some limitations in our study. First, our model is an abstraction of actual landowner behavior and not a full replication of what happens in the market. While we believe the ABM approach advances the literature on the complex market interactions that occur at the basin level in light of the introduction of a carbon market, the information and composition of the multitude of basin level markets is so asymmetrical that capturing how all markets might react is above the author's intention (and likely not possible). In our study, holding quantities demanded by the mill and carbon aggregator constant was needed for experimental control. This restriction could be relaxed in alternative study contexts, enabling the demand function to vary with price changes and allowing the model to capture potential leakage effects originating from the demand side. A caveat to this is that the specification of the demand function itself is also questionable on the scale of a single mill; this would require either an estimation of the cost function, or assumptions about percent changes in demand. Since our study is restricted to a basin with a single mill, our study cannot examine price substitution effects in secondary product markets, which could offset forest carbon gains. Rather than using a mill agent, Henderson and Abt (2016) represented demand with a demand curve and studied a mix of landowners with profit motives and landowners who aim to hold standing forests and showed significant impacts on stand age structure dynamics due to the interaction of agents within the market. In this study, all landowners here are assumed to be profit maximizers and foresee the optimal rotation for decades in the future. We addressed the desire for greater heterogeneity among agents partially by randomizing the discount rates and costs.

Our study demonstrates that forest carbon programs can significantly alter timber markets and stand age structures in the U.S. South. While these programs promote carbon sequestration, they also present economic trade-offs, with a substantial increase in prices in some scenarios. To ensure sustainable implementation, carbon markets must balance landowner incentives and mill viability. The “cat and mouse” game between carbon programs and timber markets underscores the need for adaptive, evidence-based policies and would appear to support calls from other researchers for dynamic baselines as markets participants respond to evolving incentives. A more nuanced approach that incorporates productivity improvements, shorter-term contracts, and better leakage management should enhance both the economic and ecological viability of carbon programs.

CRediT authorship contribution statement

Bruno Kanieski Da Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jesse D. Henderson:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Shaun M. Tanger:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrew R. Tilman:** Writing – review & editing, Validation, Methodology, Investigation, Funding acquisition, Conceptualization. **Stephanie Chizmar:** Writing – review & editing, Visualization, Investigation, Formal analysis, Conceptualization. **Rajan Parajuli:** Writing – review & editing, Validation, Investigation, Formal analysis. **Mohammad Marufuzzaman:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Christine C. Fortuin:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Gemini in order to improve grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Acknowledgement The authors gratefully acknowledge the generous support of the USDA Forest Service, which made this research possible through Joint Venture Agreement 22-JV-11330180-031.

Appendix A. Appendix

Table A.1. List and description of symbols and notation.

Type	Symbol	Description
Sets	i	Landowner
	s	Simulation
	t	Year
	o	Rank order from least to greatest
	m	Non-landowner agent: mill
	c	Carbon aggregator
Parameter	N	Total number of landowners
	σ	Total number of simulations

(*continued on next page*)

(*continued*)

Type	Symbol	Description
	τ	Total number of years
	γ	Minimum clearcut age
	ξ	Minimum LEV per area accepted
	δ	*Re*-offer increment
	H	Harvest cost
	C	Carbon price
Set	N	All landowners
	N'	Sampled landowners
	N^m	Landowners selected by the mill
	N^c	Landowners selected by the carbon aggregator
Landowner Attribute	a	Stand age
	y	Yield curve
	x	area inventory
	V_a	Standing volume at age a
	r	Discount rate
	b	Bid for stumpage
	d	Delivered bid
	T	Transportation cost
	E	Establishment cost
	q	Volume harvested
Aggregations	I	Total standing volume for all landowners
	Q	Total timber harvested
	$W^{m \text{ or } c}$	Demand for non-landowner agent *m* or *c*
	P	Stumpage price (volume-weighted average of accepted bids)
	$\langle P \rangle$	Expected stumpage price
	D	Average delivered price

Data availability

Data will be made available on request.

References

Arkansas Center for Forest Business, 2023. U.S. Forestry Economic Contribution by State. Available at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiMw_XvqqaLAxU378kDHa1YMr4QFnoECB8QAQ&url=https%3A%2F%2Fwww.uamont.edu%2Facademics%2FCFANR%2Fforestbusiness%2FUSForestryEconomicContributionbyState20230109.pdf&usg=AOvVaw2eGwjq88eDEm5JbvcXLqB2&opi=89978449.

Austin, K.G., Baker, J.S., Sohngen, B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Ragnauth, S., Bean, A., 2020. The economic costs of planting, preserving, and managing the worlds forests to mitigate climate change. Nat. Commun. 11 (1). https://doi.org/10.1038/s41467-020-19578-z.

Baker, J.S., Van Houtven, G., Phelan, J., Latta, G., Clark, C.M., Austin, K.G., Sodiya, O.E., Ohrel, S.B., Buckley, J., Gentile, L.E., Martinich, J., 2023. Projecting U.S. forest management, market, and carbon sequestration responses to a high-impact climate scenario. Forest Policy Econ. 147. https://doi.org/10.1016/j.forpol.2022.102898.

BloombergNEF, 2023. Long-Term Carbon Offsets Outlook 2023. Available at https://www.bloomberg.com/professional/insights/sustainable-finance/long-term-carbon-offsets-outlook-2023/.

Brandeis, C., Guo, Z., 2016. Decline in the pulp and paper industry: effects on backward-linked forest industries and local economies. For. Prod. J. 66 (1–2), 113–118. https://doi.org/10.13073/FPJ-D-14-00106.

Buongiorno, J., Zhu, S., 2013. Consequences of carbon offset payments for the global forest sector. J. For. Econ. 19 (4), 384–401. https://doi.org/10.1016/j.jfe.2013.06.005.

Business Wire, 2022. NCXs latest forest carbon program results demonstrate growth across 39 U.S. states. Available online at https://www.businesswire.com/portal/site/home.

Butler, B.J., Caputo, J., Henderson, J.D., Pugh, S., Riitters, K., Sass, E.M., 2022. Cross-boundary sustainability: assessment across forest ownership categories in the conterminous USA using the Montréal process criteria and indicators framework. Forests 13 (7), 992. https://doi.org/10.3390/f13070992.

Cubbage, F., Rubilar, R., Mac Donagh, P., Kanieski Da Silva, B., Bussoni, A., Morales, V., Balmelli, G., Hoeflich, Vitor Afonso, Lord, R., Hernández, C., Zhang, P., Thu, Ha Tran Thi, Yao, R., Hall, P., Korhonen, J., Díaz-Balteiro, Luis, Rodríguez-Soalleiro, Roque, Davis, R., Chudy, R., De La Torre, R., Lopera, G., Phimmavong, Somvang, Garzón, S., Cubas-Baez, A., 2022. Comparative global timber investment costs, returns, and applications, 2020. J. Forest Bus. Res. 1 (1), 90–121. https://doi.org/10.62320/jfbr.v1i1.16.

Daigneault, A., Baker, J.S., Guo, J., Lauri, P., Favero, A., Forsell, N., Johnston, C., Ohrel, S.B., Sohngen, B., 2022. How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob. Environ. Chang. 76. https://doi.org/10.1016/j.gloenvcha.2022.102582.

Dezember, R., 2018. Thousands of Southerners Planted Trees for Retirement. It didn't work. The Wall Street Journal. Available at https://www.wsj.com/articles/thousands-of-southerners-planted-trees-for-retirement-it-didnt-work-1539095250.

Dezember, R., 2024. An Oil Giant is Spending $100 Million to Preserve U.S. Forests. The Wall Street Journal. Available at https://www.wsj.com/finance/commodities-futures/an-oil-giant-is-spending-100-million-to-preserve-u-s-forests-24b4f4b8?msockid=31e28c27619f6cea166c98eb60066da6.

Dezember, R., Monga, V., 2021. Lumber Prices are Soaring. Why are Tree Growers Miserable? The Wall Street Journal. Available at https://www.wsj.com/articles/lumber-prices-are-soaring-tree-growers-miserable-11614177282?msockid=31e28c27619f6cea166c98eb60066da6.

Dong, L., Bettinger, P., Liu, Z., 2021. Estimating the optimal internal carbon prices for balancing forest wood production and carbon sequestration: the case of Northeast China. J. Clean. Prod. 281. https://doi.org/10.1016/j.jclepro.2020.125342.

Forisk, 2024. Local timber supply and growth-to-drain in the U.S. South. Available at https://forisk.com/blog/2024/07/18/local-timber-supply-and-growth-to-drain-in-the-u-s-south/.

Faustmann, M., 1849. Calculation of the value which forest land and immature stands possess for forestry. In: Gane, M. (Ed.), *Martin Faustmann and the Evolution of Discounted Cash Flow: two articles from the original German of 1849. Translated by W. Linnard.* (pp 27-55). Common-wealth Forestry Institute, Oxford, U.K. (1968).

Galik, C.S., Baker, J.S., Daigneault, A., Latta, G., 2022. Crediting temporary forest carbon: retrospective and empirical perspectives on accounting options. Front. Forests Global Change 5, 933020. https://doi.org/10.3389/ffgc.2022.933020.

Georgia Forestry Commission, 2018. 2018 Economic Benefits of the Forestry Industry in Georgia. Available at https://gatrees.org/wp-content/uploads/2020/01/Economic-Benefits-of-the-Forestry-Industry-in-Georgia-2018-.pdf.

Georgia-Pacific, 2023. Georgia-Pacific To Close Foley Cellulose Facility [Press release]. https://news.gp.com/2023/09/georgia-pacific-to-close-foley-cellulose-facility.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., et al., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. USA 114 (44), 11645–11650.

Guo, J., Prestemon, J., Johnston, C., 2023. Forest market outlook in the southern United States. Forest Policy Econ. 157. https://doi.org/10.1016/j.forpol.2023.103091.

Harrison, W.M., Borders, B.E., 1996. Yield prediction and growth projection for site-prepared loblolly pine plantations in the Carolinas, Georgia, Alabama and Florida (PMRC Technical Report 1996-1). In: Plantation Management Research Cooperative, Daniel B. Warnell School of Forest Resources. University of Georgia. Retrieved November 12, 2025, from. https://programs.ifas.ufl.edu/media/programsifasufledu/carbon-resources-models/docs/loblolly-plantation/lob-pine-growth-yield.pdf.

Henderson, J.D., Abt, R.C., 2016. An agent-based model of heterogeneous forest landowner decisionmaking. For. Sci. 62 (4), 364–376. https://doi.org/10.5849/forsci.15-018.

Henderson, J.D., Parajuli, R., Abt, R.C., 2020. Biological and market responses of pine forests in the US southeast to carbon fertilization. Ecol. Econ. https://doi.org/10.1016/j.ecolecon.2019.106491.

Henderson, J.D., Abt, R.C., Abt, K.L., 2024. Forest carbon under increasing product demand and land use change in the US southeast. Forest Policy Econ. https://doi.org/10.1016/j.forpol.2024.103296.

Hernandez, M., Gómez, T., Molina, J., León, M.A., Caballero, R., 2014. Efficiency in forest management: a multiobjective harvest scheduling model. J. For. Econ. 20 (3), 236–251. https://doi.org/10.1016/j.jfe.2014.06.002.

Hodges, D.G., Chapagain, B., Watcharaanantapong, P., Poudyal, N.C., Kline, K.L., Dale, V.H., 2019. Opportunities and attitudes of private forest landowners in supplying woody biomass for renewable energy. Renew. Sust. Energ. Rev. 113. https://doi.org/10.1016/j.rser.2019.06.012.

International Paper, 2023. International Paper Announces Strategic Actions [Press release]. https://internationalpaper2022rd.q4web.com/news/news-details/2023/International-Paper-Announces-Strategic-Actions/default.aspx.

International Paper, 2024. International Paper Announces Review of Strategic Options for Global Cellulose Fibers Business and Closure of Georgetown, S.C. Pulp and Paper Mill [Press release]. https://internationalpaper2022rd.q4web.com/news/news-details/2024/International-Paper-Announces-Review-of-Strategic-Options-for-Global-Cellulose-Fibers-Business-and-Closure-of-Georgetown-S.C.-Pulp-and-Paper-Mill/default.aspx.

Kanieski da Silva, B., Rezaei, F., Shaun, T., Henderson, J., McConnell, E., Sun, C., 2024. Terminal value: a crucial and yet often forgotten element in timber harvest scheduling and timberland valuation. Forest Policy Econ. 162. https://doi.org/10.1016/j.forpol.2024.103188.

Kirschbaum, M.U., 2006. Temporary carbon sequestration cannot prevent climate change. Mitig. Adapt. Strateg. Glob. Chang. 11 (5), 1151–1164.

Klemperer, W.D., Bullard, S.H., Grado, S.C., Measell, M.K., Straka, T.J., 2023. Forest appraisal and valuation. In: Forest Resource Economics and Finance - Second Edition. Stephen F. Austin State University, pp. 340–369.

Lamichhane, S., Parajuli, R., Henderson, J.D., da Silva, Kanieski, Tanger, S.M., 2025. Examining divergence in softwood lumber and timber prices in the southern United States. For. Sci. 71, 183–202. https://doi.org/10.1007/s44391-024-00012-6.

Marland, G., Fruit, K., Sedjo, R., 2001. Accounting for sequestered carbon: the question of permanence. Environ. Sci. Pol. 4, 259–268.

Mason, C.F., Plantinga, A.J., 2013. The additionality problem with offsets: optimal contracts for carbon sequestration in forests. J. Environ. Econ. Manag. 66 (1), 1–14. https://doi.org/10.1016/j.jeem.2013.02.003.

Mei, B., 2023. Carbon offset as another driver of timberland investment returns in the United States. J. Forest Bus. Res. 2 (Issue 1). www.forest-journal.com.

Mihiar, C.M., Lewis, D.J., 2023. An empirical analysis of US land-use change under multiple climate change scenarios. J. Agric. Appl. Econ. Assoc. 2 (3), 597–611. https://doi.org/10.1002/jaa2.82.

Monge, J.J., Bryant, H.L., Gan, J., Richardson, J.W., 2016. Land use and general equilibrium implications of a forest-based carbon sequestration policy in the United States. Ecol. Econ. 127, 102–120. https://doi.org/10.1016/j.ecolecon.2016.03.015.

Newman, P.H., 1988. The optimal forest rotation: A discussion and annotated bibliography. USDA For. Serv., Gen. Tech. Rep. SE-48, South-eastern Forest Experiment Station, Asheville, NC, p. 47.

Nova, M., 2024, May 20. Why Did NCX Stop the 1-Year Forest Carbon Program? NCX. https://www.ncx.com/learning-hub.

Parajuli, R., Tanger, S.M., Joshi, O., Henderson, J.E., 2016. Modeling prices for sawtimber stumpage in the South-Central United States. Forests 7 (7), 148.

Parisa, Z., Marland, E., Sohngen, B., Marland, G., Jenkins, J., 2022. The time value of carbon storage. Forest Policy Econ. 144. https://doi.org/10.1016/j.forpol.2022.102840.

Pingoud, K., Ekholm, T., Sievänen, R., Huuskonen, S., Hynynen, J., 2018. Trade-offs between forest carbon stocks and harvests in a steady state – a multi-criteria analysis. J. Environ. Manag. 210, 96–103. https://doi.org/10.1016/j.jenvman.2017.12.076.

Rossi, D.J., Baker, J.S., Abt, R.C., 2023. Quantifying additionality thresholds for forest carbon offsets in Mississippi pine pulpwood markets. Forest Policy Econ. 156. https://doi.org/10.1016/j.forpol.2023.103059.

Sartori, P.J., Schons, S.Z., Amacher, G.S., Burkhart, H., 2024. Deferred rotation carbon programs for even-aged forests: aligning landowner and societal objectives. Forest Policy Econ. 168. https://doi.org/10.1016/j.forpol.2024.103295.

Sedjo, R.A., Wisniewski, J., Sample, A.V., Kinsman, J.D., 1995. The economics of managing carbon via forestry: assessment of existing studies. Environ. Resour. Econ. 6 (2), 139–165.

Stavins, R.N., Richards, K.R., 2005. The Cost of U. S. Forest-Based Carbon Sequestration. In: Pew Center on Global Climate Change.

Tahvonen, O., & Rautiainen, A. (2017). Economics of forest carbon storage and the additionality principle. Resour. Energy Econ., 50, 124–134.hhttps://doi.org/10.1016/j.reseneeco.2017.07.001.

Tanger, S.M., da Silva, B.K., Polinko, A.D., McConnell, T.E., McDill, M.E., 2022. Estimating stand-level carbon supply curves for loblolly pine and Douglas-fir plantations. J. For. 121 (2), 125–134. https://doi.org/10.1093/jofore/fvac036.

Trencher, G., Nick, S., Carlson, J., Johnson, M., 2024. Demand for low-quality offsets by major companies undermines climate integrity of the voluntary carbon market. Nat. Commun. 15 (1), 6863. https://doi.org/10.1038/s41467-024-51151-w.

USDA Forest Service, 2023. Forest Inventory and Analysis Database. Available at https://apps.fs.usda.gov/fia/datamart/datamart.html.

Verra, 2013. VM0003. Methodology for improved Forest management through extension of rotation age, v1.2 (methodology), Sectoral Scope 14. Agriculture, Forestry, Land Use Ecotrust, Verra, Portland.

Verra, 2022. Verra Defers Updates to the VCS Program. Available at https://verra.org/verra-defers-updates-to-the-vcs-program/. Accessed in 2/2/2025.

Wear, D.N., Coulston, J.W., 2015. From sink to source: regional variation in U.S. forest carbon futures. Sci. Rep. 5. https://doi.org/10.1038/srep16518.

WestRock, 2022, April 7. WestRock to Close Panama City, Florida, Paper Mill [Press release]. https://ir.westrock.com/press-releases/press-release-details/2022/WestRock-to-Close-Panama-City-Florida-Paper-Mill/default.aspx.

Yin, R., Newman, D.H., 1997. Long-run timber supply and the economics of timber production. For. Sci. 43 (1), 113–120. https://doi.org/10.1093/forestscience/43.1.113.

Zhang, D., 2021. From industrial to institutional timberland ownership. In: From Backwoods to Boardrooms. Oregon State University Press.