# Quantifying Additionality Thresholds for Forest Carbon Offsets in Southern Pine Pulpwood Markets

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***Abstract:*** There is an urgent need to examine additionality in a market context. To this end, our analysis focuses on the extent to which deferred harvests of pulpwood as an offset source can achieve additionality across a large wood-producing region like the U.S. South. Recent consideration of additionality in the context of short-term deferred harvest contracts relies in part on project-scale assessments of harvest likelihood. However, these regression-based predictions of harvest likelihood may ignore dynamic market forces that drive landowner willingness to either harvest their forest or delay harvest and continue storing carbon. Our analysis differs from previous approaches by explicitly accounting for market forces, including both the supply-side dynamics of the forest resource base and the potential trajectories of roundwood demand across a region. Our projections illustrates how additionality thresholds for pine pulpwood depend critically on the trajectory of pulpwood demand. We present estimates of annual harvests and sequestration with and without offset market activity at a broad spatial scale. Results indicate that falling demand for pine pulpwood can generate enough sequestration to meet or exceed the sequestration realized under an offset market.

***Keywords:*** timber markets, sawtimber, pulpwood, aboveground carbon, elasticity, harvest likelihood.

***JEL Classification:*** L73, Q23, Q54

## 1. Introduction

Private sector interest in land-based climate mitigation strategies has grown in recent years, driven in part by Intergovernmental Panel on Climate Change (IPCC) reports that emphasize the important role of increasing the land carbon sink for achieving ambitious climate stabilization goals (IPCC, 2022). Increased focus on land-based mitigation strategies has mobilized climate finance and led to a re-emergence of voluntary forest carbon offset programs. These programs compensate forest managers for activities such as forest preservation and improved forest management that provide *additional* carbon sequestration benefits relative to a business-as-usual scenario (Austin et al., 2020). Despite significant private sector interest, offset markets have not reached a potential consistent with investment pledges, in part due to factors such as additionality, leakage, and permanence (Murray et al., 2007). These factors raise credibility concerns over offset market participation and may limit future offset market development.

Notably, the longer-term contracts associated with many forest carbon offset programs have limited participation and raise important concerns regarding the long-term carbon storage potential of these offsets in the face of disturbance risk. In 2021, new voluntary markets emerged that offer flexible short-term contracts (1-3 years) for deferring forest harvests temporarily, thus providing a temporary source of emissions reduction. Companies like the Natural Capital Exchange (NCX) or Sky Harvest use spatial analytics and regression-based predictions of harvest likelihood to determine market eligibility (e.g. Prestemon and Wear, 2000). Interpolated harvest likelihood parameters can be used to determine potential additionality for forestland owners applying to short-term offset programs. Eligible forestland owners with a high probability of harvesting have the ability to receive payment for entering a short-term harvest deferral contract. These contracts are intended to offer compensation for the *additional* change in temporary carbon sequestration between the assumed harvest age and the end of the contract term.

The introduction of shorter-term offset contracts like these could substantially improve landowner interest in harvest deferrals and increase offset market participation. The summer 2021 NCX auction resulted in 904,000 acres enrolled, providing a reported 500,000 $MtCO_2$ equivalent in offsets. This provided sequestration revenues for 577 landowners in 16 states, representing a 484% increase in participation from the Spring 2021 auction. Despite this rapid development, questions remain regarding the additionality of short-term harvest deferral contracts, as well as broader market tradeoffs. The relative ease of landowner participation in carbon offset markets raises concern over whether *additional* carbon is being stored via the offset program, above the storage realized under business-as-usual market conditions.

Separate from the introduction of forest carbon offset markets, recent market developments have had a positive impact on the average harvest age of forests in the Southern U.S. This trend has occurred due to both rising demand for southern sawtimber and growth of the wood pellet industry. The former has shifted harvests away from younger trees typically used for pulpwood to a higher proportion of harvests for chip-and-saw and sawtimber (i.e. older trees). Growth in the wood pellet industry has created a high market demand for mill residuals, which increases profits for sawmills and further stimulates the derived demand for the sawtimber used primarily for lumber production. With an increasing demand for larger-diameter roundwood products like sawtimber, the baseline level of carbon storage increases as trees age to accommodate new market demands. In such situations, regression-based prediction of harvest likelihood may be inadequate for establishing baseline additionality thresholds (e.g., harvest likelihood by forest type and age class), especially in future periods. When baseline levels of carbon storage increase as a result of a demand-side shock in the sawtimber market, there is less potential for forest carbon offsets to store additional carbon beyond what the roundwood market can already provide.

This paper investigates the potential for roundwood market dynamics to undermine the added value of forest carbon offset markets, and offers ideas for improving the determination of landowner eligibility in an offset program. We develop a simple two-product conceptual model of market dynamics and carbon sequestration (where products are distinguished by the typical harvest age). We use a detailed bioeconomic model of the Southern U.S. forest sector to simulate scenarios with and without a carbon offset incentive and at different levels of pulpwood demand. Our results to illustrate the importance of dynamic additionality considerations that reflect interactions between products markets and the presence of offset incentives.

This manuscript proceeds as follows. First, we briefly summarize relevant literature on additionalility in the following section, highlighting contributions of this work. In section 2, we develop a conceptual framework that describes additionality as a market concept that is dynamic in nature, deviating from the treatment of additionality as a project-scale consideration that is fixed over time. In Section 3, we introduce a bioeconomic model that projects timber inventory, harvests, and carbon storage across the southern U.S. under alternative demand scenarios. We then develop a scenario design to simulate potential harvest profiles in spatially disaggregated regions in the Southern U.S for four industrial timber products: 1) smaller-diameter pine pulpwood, 2) larger-diameter pine sawtimber, 3) smaller-diameter hardwood pulpwood, and 4) larger-diameter hardwood sawtimber. In Section 4, we present our results with particular attention to pine market activity. In this section, we describe the sensitivity of southwide harvests of pine roundwood and aboveground carbon storage to varying degrees of offset market activity under constant and falling demand for pine pulpwood. In section 5, we discuss the policy and market implications of our results, the limitations of our analysis, and directions for further research.

### *1.1. Mechanisms for achieving additionality*

Additionality is fundamentally a market problem involving asymmetric information (Mason and Plantinga, 2013), where landowners conceal their private opportunity cost of holding land in a forested use (like timber production) while buyers or brokers of carbon offset credits must learn about this cost for any given landowner via the design of a cost-revealing contract. The design of these optimal contracts hinders the first-best market outcome (one where the social benefits of sequestration are internalized) and is difficult to implement in practice. Instead, brokers rely on predictive regression models of harvest probability to approve landowners who apply to enroll their land in the offset program (e.g. Prestemon and Wear, 2000). Excluding any potential methodological issues with these probability models, the brokers themselves determine the threshold prediction under which a landowner is deemed ineligible for the program. This subjectivity threatens the reliability and validity of additional carbon sequestered via the offset market mechanism.

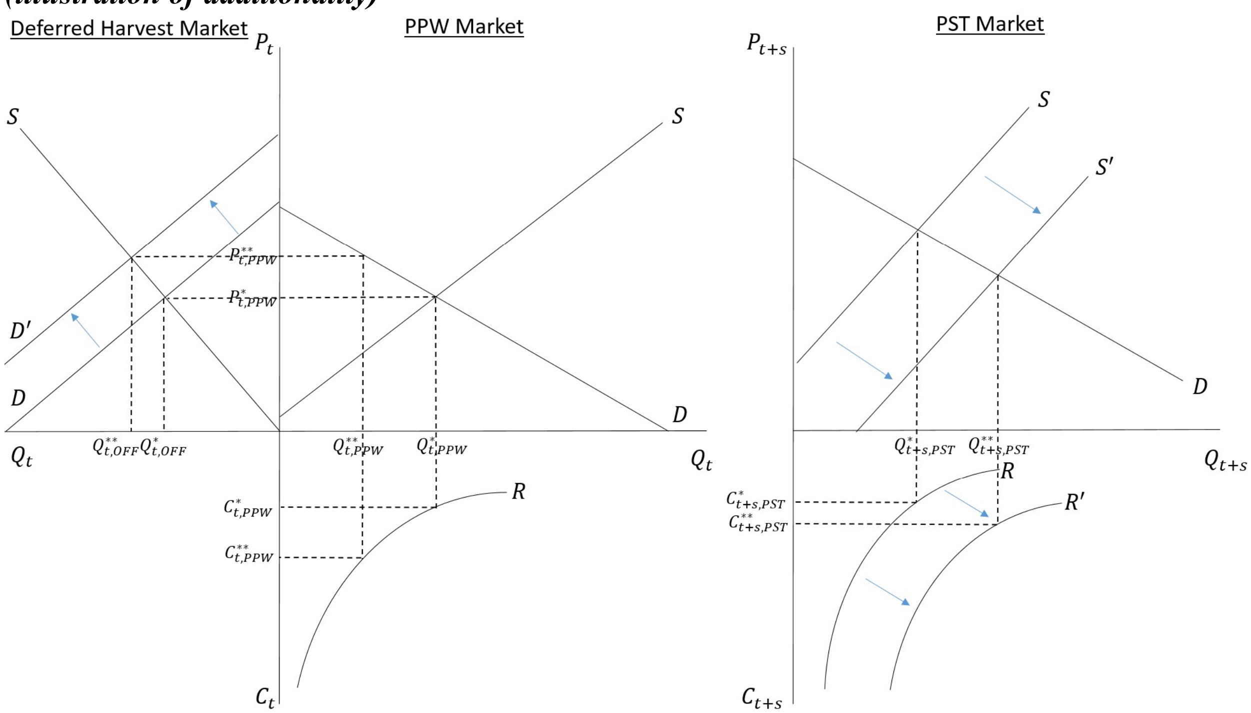
Public policies to ensure additionality are available but also limited in their effectiveness. Notably, Tahvonen and Rautiainen (2017) show that first-best solutions to the additionality problem include a land tax, but this solution assumes that the parameters of additional carbon storage at the stand-level are known and enforceable by the tax planner. In cases where market-level forces interact with rents for alternative land uses, a second-best outcome can be achieved via the use of a site productivity tax. This outcome is also dominated on efficiency grounds by the market solution under complete information. This highlights the importance of examining additionality as a result of market-based allocations and the possibility for baselines to be determined by market forces that are subject to change over time.

Several empirical analyses have been used to quantify harvest probabilities as a function of stand age, forest type, distance indicators and other physical factors (Prestemon and Wear, 2000; Zhao et al., 2020). Other approaches include the development of project plans that with net present value comparisons to demonstrate that a management change would not have been adopted in the absence of the environmental market incentive (Baker et al., 2019). In contrast, we explicitly recognize that additionality is a market concept and is dynamic in nature, which deviates from typical treatment of additionality at the project-scale. Market-based allocations of harvest patterns are subject to change over time, and this may affect offset performance. Much like leakage is considered a market factor that affects offset performance, our framework treats additionality as an outcome that is fundamentally driven by market allocations of harvest patterns and land use that are subject to change.

## 2. Conceptual Framework

Our conceptual framework relates offset market activity with the growth rate of the timber growing stock. We specifically focus on pine harvests, the resulting inventory of roundwood, and the associated aboveground carbon storage of that inventory. Offset market activity is represented by the market for deferred pine pulpwood harvests. When offset market brokers enable the transaction of offset credits, there is a rise in the demand for deferred harvests of younger, smaller-diameter trees. This can best be understood with an illustration as in Figure 1, where we highlight the effects of a positive demand shock for the deferred harvest of a smaller-diameter roundwood product (pine pulpwood or "PPW") in time $t$ on the market industrial uses of PPW and on the market for a larger-diameter roundwood product (pine sawtimber or "PST") in time $t+s$. In Figure 1, we show linearized supply and demand curves to assess the effect of a carbon offset market on realized carbon storage across two time periods: year $t$ and year $t+s$.

***Figure 1: The effects of a forest carbon offset market via shifting demand for deferred harvest (illustration of additionality)***

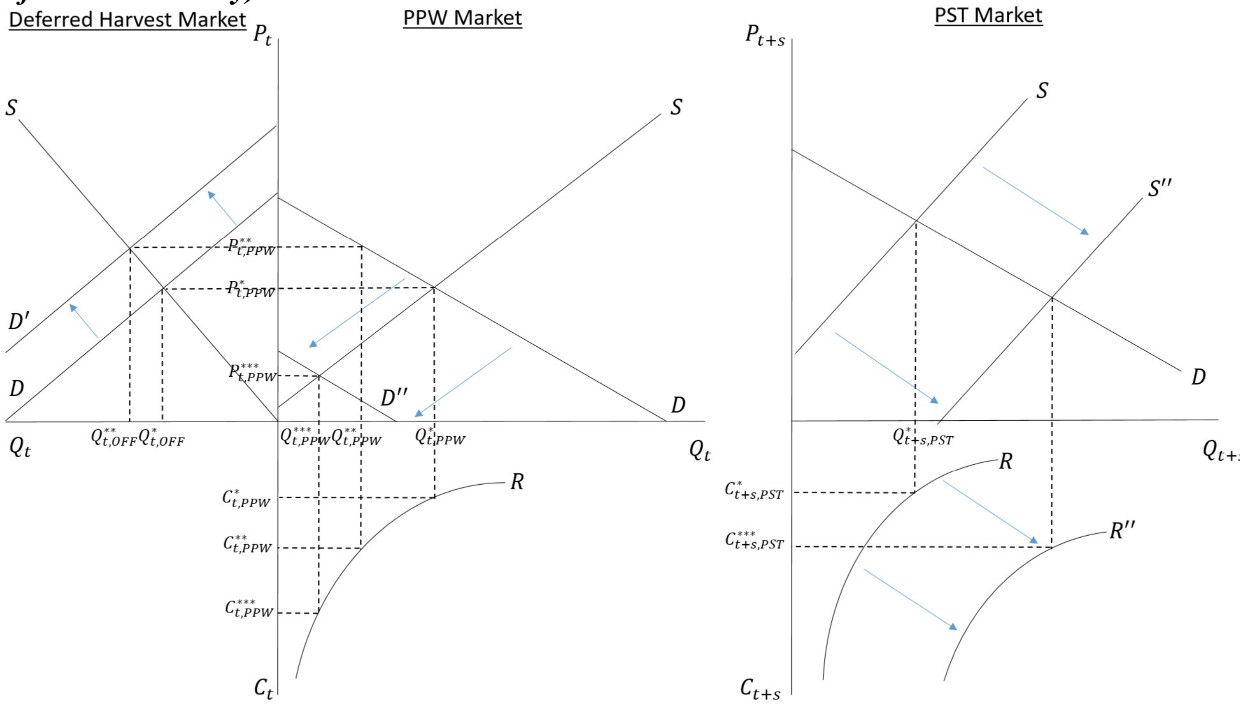



Let the relationship $R$ define the tonnage of carbon stored aboveground ($C_{jt}$) given a level of annual harvest ($Q_{jt}$). We see in Figure 1, that with the introduction of an offset market, there is a positive demand for delaying the harvest of PPW (in the Deferred Harvest Market), raising the price of PPW in the market for industrial uses of the roundwood (from $P^{*}_{t,PPW}$ to $P^{**}_{t,PPW}$). This higher price generates an excess supply which is repurposed to achieve carbon sequestration and so is kept as part of the growing stock of pine pulpwood $\Big(Q^{**}_{t,OFF} = Q^{**}_{t,PPW}\big(P^{**}_{t,PPW}\big) -$

$Q_{t,PPW}^{D}\left(P_{t,PPW}^{**}\right)\Big)$. This translates directly into a reduction in the quantity of PPW harvested (from $Q_{t,PPW}^{*}$ to $Q_{t,PPW}^{**}$) and a rise in the level of carbon stored in pulpwood-aged forests (from $C_{t,PPW}^{*}$ to $C_{t,PPW}^{**}$). The excess supply of PPW generated by this demand shift in year $t$ (and the prevailing market price above the equilibrium rate) is repurposed to achieve the goals of the offset market (represented by the volume of deferred harvest $Q_{t,OFF}^{**}$).

With the negative supply shock in the PPW market in period $t$, the forgone harvest of PPW ($F_{PPW,t}$) is left to grow into larger size classes such that the standing inventory of PST in time $t+s$ is: $V_{io,PST,t+s} = V_{io,PST,t} + \Delta V_{io,PST,t+s} - Q_{io,PST,t}^{*} + F_{io,PPW,t} + \Delta F_{io,PPW,t+s}$. That is, the volume of PST available in time period $t+s$ includes both the baseline trajectory of PST inventory growth less removals in the previous period ($V_{io,PST,t} + \Delta V_{io,PST,t+s} - Q_{io,PST,t}^{*}$), plus the forgone PPW harvest in the initial period ($H_{io,PPW,t}$), plus the growth of that forgone harvest that remains in the growing stock ($\Delta F_{io,PPW,t+s}$). This larger volume of inventory for PST available is represented in Figure 1 by a positive supply shock in the PST market from $S$ to $S'$ is in time period $t+s$. The forgone pulpwood harvest also improves the capacity for carbon storage in larger diameter products in subsequent years. This is reflected in Figure 1 by a positive shift from $R$ to $R'$ in the PST market in year $t+s$. This would change the equilibrium quantity in year $t+s$ from $Q_{PST,t+s}^{*}$ to $Q_{PST,t+s}^{**}$, resulting in a fall in the equilibrium price of PST and an increase in carbon stored in PST-aged forests from $C_{t+s,PST}^{*}$ to $C_{t+s,PST}^{**}$.

***Figure 2: The effect of a forest carbon offset market with shifting PPW demand (illustration of no additionality)***




However, it is possible that even without access to carbon offset revenues, additional carbon can be stored beyond the initial equilibrium under changing market conditions. For example, *after* the offset market has settled and the deferred harvest levels have been set at $Q^{**}_{t,OFF}$, forest landowners may face a decline in the demand for PPW (for example, they may experience a shift from $D$ to $D''$ as in Figure 2). With a drop in the demand for PPW in year $t$, the equilibrium harvest of PPW in period $t$ drops from $Q^{*}_{t,PPW}$ to $Q^{***}_{t,PPW}$ (corresponding to higher levels of aboveground storage in PPW-aged forests than what would be achieved under the offset market alone, $C^{***}_{t+s,PPW} > C^{**}_{t+s,PPW}$). Given the higher demand for deferred harvest of pulpwood-aged forests ($D'$), landowners would be paid to produce the level of sequestration $C^{**}_{t,PPW}$ (and receive the producer surplus in the deferred harvest market). However, once the new demand for industrial uses of PPW is revealed ($D''$), landowners would choose to produce a higher level of sequestration $C^{***}_{t,PPW}$ (and receive the producer surplus in the PPW market).

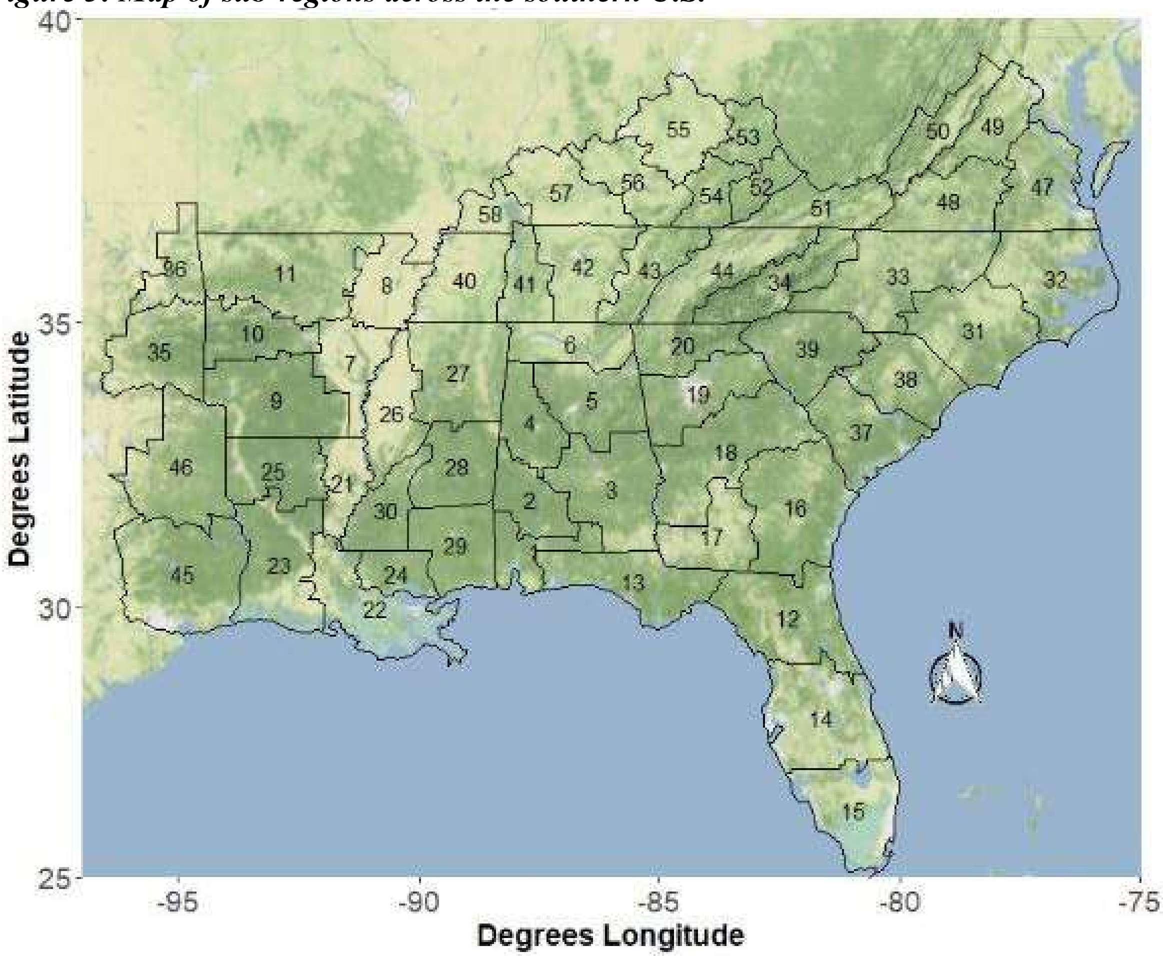
In this case, there would be a corresponding positive shift in the $R$ curve for PST in year $t + s$. If large enough, this can induce greater sequestration capacity across PST-aged forests than what could occur under an offset market alone; illustrated by a shift from $R\ to\ R''$ in Figure 2 rather than from $R\ to\ R'$ as was the case for the introduction of an offset market in Figure 1. The equilibrium harvest of PST in period $t + s$ rises from $Q^{*}_{t,PST}$ to $Q^{***}_{t,PST}$ (similarly corresponding to a greater level of aboveground storage in PST-aged forests, $C^{***}_{t+s,PST} > C^{**}_{t+s,PST}$). In this case, the carbon offset market may be less effective at offsetting emissions in both PPW- and PST-aged forests if the negative shift in demand for PPW is large enough to induce higher levels of aboveground storage than what could occur under the offset market alone after it has settled. In other words, it is possible for demand-side dynamics to achieve additionality even without the introduction of a forest carbon offset market, but it is also possible for demand-side dynamics to counteract the effectiveness of additionality actually achieved via the offset program.

In general, there may be cases where eligible landowners in the offset program are approved based on an assumption of a market in equilibrium at $(Q^{*}_{t,PPW}, Q^{*}_{t+s,PST})$. If there is an unanticipated demand shock from $D$ to $D''$, forest carbon offset markets will not achieve additional carbon storage beyond what demand-side dynamics are already capable of providing. It may also be the case that negative demand shifts for industrial uses of PPW may not be large enough to undermine the effectiveness of the offset market at achieving additionality. To simulate the likely net effects and examine sensitivities of this framework to offset market activity, we turn next to a simulation-based scenario design.

## 3. Computational Model

We use the Sub-Regional Timber Supply (SRTS) model (Abt et al., 2009) to simulate the effects of an offset market and a product-specific demand shift on equilibrium harvests and carbon storage across large and small timber products. The model is initialized using the Forest Inventory and Analysis data (Burrill et al., 2021) and the Timber Products Output data (Coulston et al., 2018) for the 58 sub-regions across the southern United States displayed in Figure 3.

***Figure 3: Map of sub-regions across the southern U.S.***




The SRTS model specifies a market equilibrium for softwood timber in the southern United States. Specifically, the model defines a partial equilibrium framework with a dynamic supply function that relates changes in the growing stock inventory of timber products to annual harvest levels. Supply is indexed by sub-region ($i$), product type ($j$), and ownership group ($o$), for each year ($t$). The model solves for a market-clearing price and harvest level for each softwood timber product in each year of the projection. These prices and quantities are represented by the solution to the following partial equilibrium problem:

$$Q_{iojt}^{S}\left(P_{jt}, V_{iojt}\right) = \alpha P_{jt}^{\gamma_{oj}} V_{iojt}^{\tau_{oj}}$$
$$Q_{jt}^{D}\left(P_{jt}\right) = \beta P_{jt}^{\epsilon_{j}}$$
$$\sum_{i}\sum_{o} Q_{iojt}^{S}\left(P_{jt}, V_{iojt}\right) = Q_{jt}^{D} \tag{1}$$

The function $Q_{iojt}^{S}\left(P_{jt}, V_{iojt}\right)$ is the supply function for sub-region $i$, roundwood product type $j$, and ownership group $o$, in each year $t$. It gives the quantity of timber supplied ($Q_{iojt}^{S}$) as a function of its price ($P_{jt}$) and the growing stock inventory volume ($V_{iojt}$). The function $Q_{jt}^{D}\left(P_{jt}\right)$ is the market demand curve for product type $j$ in year $t$. It gives the quantity of timber demanded ($Q_{jt}^{D}$) as an inverse function of its price ($P_{jt}$). The parameters $\alpha$ and $\beta$ are supply and demand shifters, the parameter $\gamma_{oj} > 0$ represents the price elasticity of supply, and $\epsilon_{j} < 0$ represents the price elasticity of demand. The parameter $\tau_{oj} > 0$ represents the inventory-supply elasticity. It gives the percentage increase in quantity supplied from a one percent increase in growing stock inventory. The market supply for each product and year is given by the summation of supply functions across sub-regions and ownership groups, $\sum_{i}\sum_{o} Q_{iojt}^{S}$. In equilibrium, this value is equal to the market demand. This market solution ($Q_{jt}^{*}, P_{jt}^{*}$) is found using a bisection algorithm (e.g. Miranda and Fackler, 2002) and defines harvest levels for each product type $j$ in each year $t$ of the simulation. The equilibrium harvest level for an owner's harvest of product $j$ within each sub-region is given by the quantity supplied at the market clearing price: ${Q_{iojt}^{S}}^{*}\left(P_{jt}^{*}, V_{iojt}\right)$.

To allocate the market solution across forest management types ($m$) and age classes ($g$), a lexicographic goal program (Ignizio, 1985; Kornbluth, 1973) is solved for each sub-region and year of the market projection.[1] Let $x_{gm}$ represent the volume of harvest relative to the growing stock volume within each management type $m$ and each age class $g$. The following set of targets represent an ownership group's objective to meet the total harvest in sub-region $i$ in year $t$ of the projection:

$$\sum_{g=3}^{11}\sum_{m=1}^{5} c_{jgm}x_{gm} + \mu_j - \nu_j = Q_j^{S^*} \quad \forall j = 1, \ldots, J \tag{2}$$

In the set of $J$ constraints in equation (2), the coefficients $c_{jgm}$ represent the proportion of growing stock inventory in each forest management type and in each age class that is available as product type $j$. The product $c_{jgm}x_{gm}$ provides the volume of product $j$ harvested within each the volume harvested in each forest management type and in each age class.[2] The slack variable $\mu_j$ represents the volume of product $j$ harvested below the equilibrium level, while the slack variable $\nu_j$ represents the volume of product $j$ harvested above the equilibrium level. When $\mu_j = \nu_j$ the volume of product $j$ harvested is equal to the market equilibrium.

To control harvests from deviating too far from historical patterns of removals, the model specifies an additional set of targets to control the removal-to-inventory intensity. The additional

[1] For a 10-year projection with 58 sub-regions and 2 ownership groups, this goal programming problem is solved 1160 times. Starting inventory classes are given in 5-year increments. The model allocates starting inventory to annual age classes and runs on a one-year time step with output summed to 5-year age classes each year. A minimum of age of 10 is assumed for volume to be of merchantable size.

[2] Note that when summed across product types, the proportions of volume in each age class and forest management type must sum to 1.0 jcjgm=1.0.

set of targets are included to reflect existing harvest patterns across forest management types and age clases by sub-region, ownership group, and product:

$$x_{gm} + s_{gm}^1 - s_{gm}^2 = \frac{Q_{gm,t-1}^{S}{}^*}{V_{gm,t-1}} \qquad \forall g = 3, \ldots, 11 \;\&\; \forall m = 1, \ldots, 5 \tag{3}$$

In equation (3), the target set of 45 targets $\frac{Q_{j,t-1}^{S}{}^*}{V_{j,t-1}}$ represents the removal to inventory ratio in the previous year of the projection. The first set of slack variables $s_{gm}^1$ represent negative deviations from the removal-to-inventory ratio from the previous year's removal-to-inventory ratio and the second set of slack variables $s_{gm}^2$ represent positive deviations from the previous year's removal-to-inventory ratio. When $s_{gm}^1 = s_{gm}^2$, the removal-to-inventory ratios in the current year for a given sub-region and owner group are equal to the ratio from the previous year. The set of targets in (3) ensure that, for example, the relative intensity of harvests on pine plantations by corporate owners remains higher than the harvest intensities for other owners and forest types as it has historically.

The goal programming procedure specifies a linear programming problem which minimizes the weighted sum of absolute deviations from each of the targets subject to (2) and (3):

$$\underset{\{x_{gm}, \mu_j, \nu_j, s_{gm}^1, s_{gm}^2\}}{\text{minimize:}} \sum_{j=1}^{J} W_j(\mu_j + \nu_j) + \sum_{g=3}^{11} \sum_{m=1}^{5} Z_{gm}(s_{gm}^1 - s_{gm}^2) \tag{4}$$

Here the $W_j$ represent the relative importance of meeting the targets defined in equation (2) and the $Z_{gm}$ represent the relative importance of meeting the targets defined in equation (3). Additional non-negativity constraints are placed on each of the slack variables ($\mu_j \geq 0, \nu_j \geq$

$0, s_{gm}^1 \geq 0, s_{gm}^2 \geq 0$). A set of lower bounds is also defined for each of the removal-to-inventory ratios given bio-physical constraints regarding the amount of volume available in each forest management type and age class. The portion of the solution which represents the removal-to-inventory ratios $x_{gm}^*$ is multiplied by the growing stock inventory to obtain an approximation of the market equilibrium for product $j$ as the sum of harvests across each forest management type and across each age class: $H_j^* = \sum_g \sum_m x_{jgm} * V_{gm}$. Solving the goal program in (4) for each sub-region and each ownership group in each year of the projection, provides us with a pathway of harvests $H_{iojt}^*$.

Following each year's market solution and harvest allocation across these contingencies as determined by the goal program ($H_{iojt}^*$), the inventory volume in the next period ($V_{ioj,t+1}$) is grown according to the following transition equation:

$$V_{ioj,t+1} = V_{iojt} + \Delta V_{iojt} - H_{iojt}^* \tag{5}$$

Where $\Delta V_{iojt}$ is the average annual growth in merchantable timber volume, net of mortality, for each sub-region, ownership group, and product type. Each subsequent year of the simulation introduces new inventory volumes $V_{iojt}$, which shifts the supply curve for each sub-region, product class, and ownership group accordingly. Land-use change in the model is endogenously determined by land rents. With each new set of prices, land use change is determined and inventory is updated before the new market equilibrium is computed. Similarly, the mass of aboveground carbon storage ($C_{iojt}$) is a function of the standing inventory and is tracked alongside estimates of annual inventory volume, based on equations reported by Foley (2009). We follow the development of aggregate southwide aboveground carbon storage resulting from the market equilibrium over the course of the simulation: $C_t^* = \sum_{ioj} C_{iojt}$.

We seek the effects of an offset market on the equilibrium harvest quantities of pine timber products and the resulting levels of aboveground carbon storage. If the introduction of forest carbon offsets can decrease the willingness of landowners to harvest their timber given increases in their growing stock, this translates to a new source of competing demand for timber that raises the market price above the equilibrium level ($P_{jt}^{**} > P_{jt}^{*}$). Given that this higher price will translate into excess timber supply $\left(Q_{iojt}^{S}\left(P_{jt}^{**}; V_{iojt}\right) - Q_{jt}^{D}\left(P_{jt}^{**}\right)\right)$ and a repurposed use of that excess supply to remain as growing stock, it will affect different timber products, regions, and owner-groups differently, thereby resulting in uncertain levels of carbon storage. We focus our results on the net effects of offset markets on southwide harvests and carbon storage.

### *3.1. Simulation and scenario design*

In our scenario design, forest carbon offset markets are represented by the relative importance of meeting the market equilibrium harvest level of pine pulpwood *after* it is defined and set as a target for the goal program as in (2). This translates into a re-prioritization of competing objectives in the goal program which allows for PPW harvests to deviate well below the market equilibrium as we have shown can occur when offset markets increase the bidding competition for younger-aged trees. With this scenario design, we are illustrating the efficacy of offset markets in achieving additionality in an environment characterized by falling demand for pine pulpwood.

There are two broad classes of primary pine timber products commonly harvested in the south, broken up by DBH class: 1) pine pulpwood (5-9" DBH) which is used primarily to supply pulp or paper facilities or biomass energy facilities, and 2) pine sawtimber (≥9" DBH) which is used for the manufacturing of lumber, veneer, or as utility poles. Hardwood pulpwood ("HPW") and hardwood sawtimber ("HST") products are also included in the projection (see Table 1) and in the determination of harvest according to problem (4), but we focus our results on the projected outcomes in the two pine product markets. All softwood and hardwood inventory is used to compute southwide levels of aboveground carbon storage.

Specifically, we will simulate the following four scenarios where forest carbon offset markets may or may not impact the pulpwood market:

1) Constant demand with no offset market activity ("CONST-BASE"). All $W_j = 1{,}000$.
2) Constant demand with offset market activity that impacts the PPW market only ("CONST-CARB"). $W_{PPW} = 1, W_{PST} = 100{,}000, W_{HPW} = 1{,}000, W_{PST} = 1{,}000.$
3) Falling demand for PPW with no offset market activity ("SHIFT-BASE"). All $W_j = 1{,}000.$
4) Falling demand for PPW with offset market activity that impacts the PPW market only ("SHIFT-CARB"). $W_{PPW} = 1, W_{PST} = 100{,}000, W_{HPW} = 1{,}000, W_{PST} = 1{,}000.$

In the scenarios where offset markets are active ("CONST-CARB" and "SHIFT-CARB"), they begin to adjust harvests beginning in year 2022 and continue to impact harvest volume throughout the projection. In the "CONST-CARB" and "SHIFT-CARB" scenarios, we expect the goal program to solve for a PPW harvest level below the market equilibrium since it is defined to be relatively less important than achieving equilibrium in the PST market and the markets for hardwood products (HPW and HST). Each of the falling PPW demand scenarios considers the case where we see a declining demand for PPW by a magnitude of 3% per year. This assumes a decrease in the quantity demanded of PPW from 2728 MMCF per year in 2020 to 2012 MMCF per year by 2030 and 1094 MMCF by 2050. Across all scenarios, the quantity of PST demand is held constant at its current level of 3028 MMCF per year. Each scenario keeps constant the goal weights on harvest intensities by age class and forest type ($Z_{gm} = 1$).

Table 1, we list the price elasticities of supply and demand as defined in equation (1), as well as inventory-supply elasticities which characterize the market for each pine roundwood product. The elasticities are specified based on a meta-analysis of empirical studies. We also present in Table 1 the proportion of each roundwood product that is assumed available for offsetting the demand for pulpwood (cull factors). Additional assumptions of the market environment that we hold constant for each scenario include: 1) an assumptions about the effects of carbon fertilization on the growth rate of pine plantations at the sub-regional level (see Henderson et al., 2020), 2) an assumption that 30% of volume from PST sized trees (e.g. tops/limbs/cull) are utilized as PPW, 3) an assumption that 35% of PST residuals (from manufacturing) are available as PPW feedstock, and 4) that forestland-use change is characteristic to "business-as-usual" macroeconomic conditions (Nagubadi and Zhang, 2005; Rossi et al, 2022). We also assume that trees are not of merchantable age until they are at least 10 years old.

***Table 1 – Timber product definitions and baseline elasticities in model simulations***

| Product Type | Size Class (DBH) | Percent of harvest available as pulpwood | $\epsilon_j$ | $\gamma_{corp,j}$ $(\tau_{corp,j})$ | $\gamma_{corp,j}$ $(\tau_{noncorp,j})$ |
|---|---|---|---|---|---|
| PPW | 5”-9” | 100% | 0.65 | 0.45 (0.85) | 0.30 (0.80) |
| PST | ≥9” | 30% | 0.50 | 0.51 (0.66) | 0.32 (0.70) |
| HPW | 5-11” | 100% | 0.35 | 0.54 (0.61) | 0.33 (0.71) |
| HST | ≥ 11" | 35% | 0.40 | 0.52 (0.61) | 0.31 (0.71) |

## 4. Results

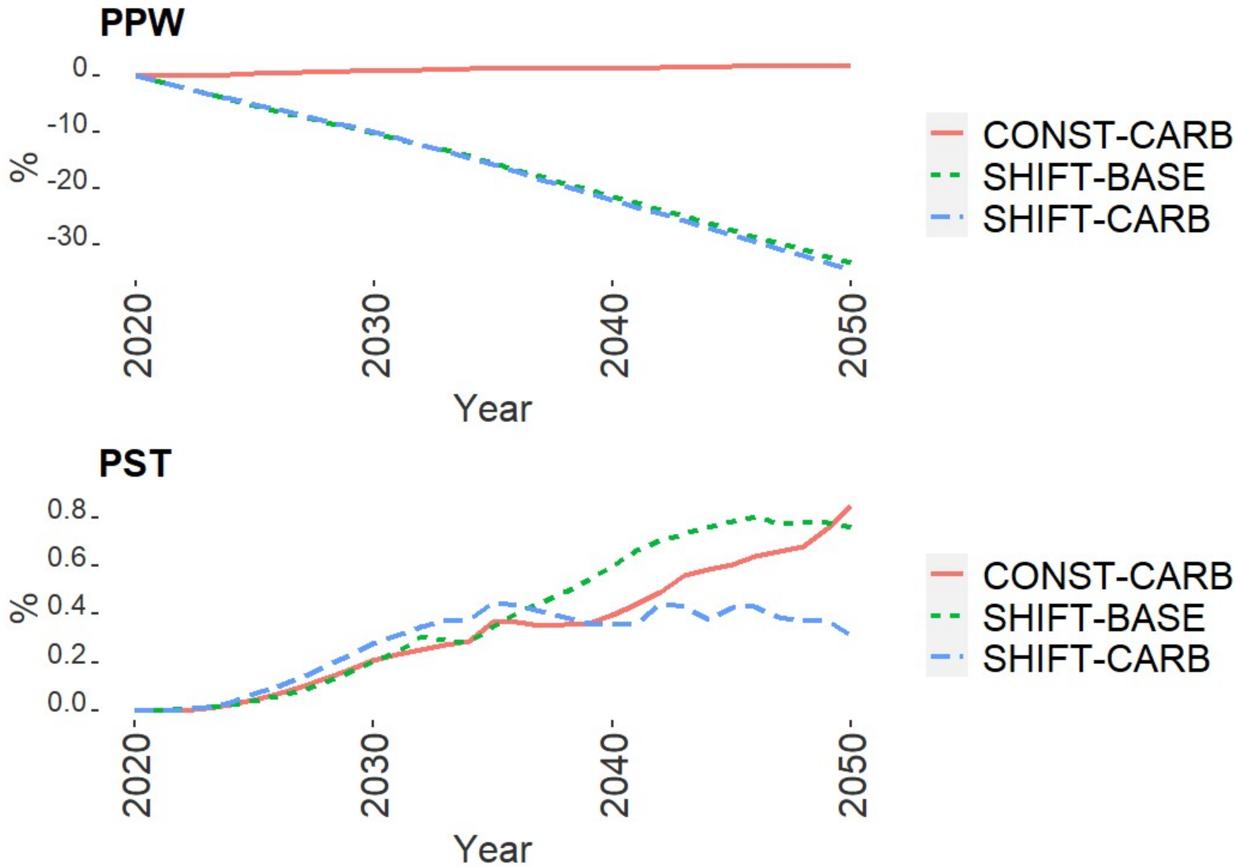
Our scenario design simulated the effects of varying intensities of carbon offset market activity. Under the “CONST-BASE” and “SHIFT-BASE” scenarios, there is no offset market activity, so product harvest weights are unchanged from their baseline levels ($W_j = 1{,}000$). Under the “CONST-CARB” and “SHIFT-CARB” scenarios, harvest levels in the PPW market are consistently lower than the market equilibrium. This illustrates the simulated capacity for offset markets to defer the harvests of younger forests and contribute to larger inventory of older sawtimber-sized logs in later years. Not surprisingly, the scheduling of a 3% per year annual decrease in PPW demand (“SHIFT-BASE” and “SHIFT-CARB”) will lower annual harvests of PPW over time and similarly contribute to an increase in the growing stock of sawtimber-sized logs. The scenarios characterized by negative shifts in PPW demand demonstrate how demand shifts in the roundwood market can limit the additional carbon storage achieved by offset market activity.

Relative to the constant demand scenario with no offset market activity (“CONST-BASE”), the “CONST-CARB” scenario displays only a slightly larger level of pine pulpwood harvested through 2050 (1.6% larger by 2050). However, this scenario also provides 0.5% more aboveground carbon storage by year 2050. The capacity for the offset market alone to increase both industrial pulpwood harvest and carbon storage is related to the increase in growing stock inventory which accompanies harvest deferrals. When pulpwood harvests are deferred due to offset market activity, the supply curve for pulpwood experiences a positive supply shift in subsequent years, thereby raising market-driven harvest targets.

When forest carbon offset markets are affect pine pulpwood harvest but demand is constant across all roundwood products, we see that harvests of pulpwood decrease substantially. Relative to the “CONST-BASE” scenario, the “SHIFT-BASE” scenario shows that PPW harvests will decline by 9.8% by 2030 and by 28.3% by 2050. This deferral leads to 0.2% more carbon storage per year through 2030 and through 2050 (corresponding to around 14.5 additional metric tons of carbon storage in year 2050). This illustrates the effect of offset markets in deferring harvests of younger pine forests in order to sequester additional carbon dioxide across the southern region. However, when demand for PPW is falling at a rate of 3% per year (as in the “SHIFT-CARB” scenario), the level of carbon storage across the southern region is limited to a level 0.3% lower than the baseline scenario (providing 608 million metric tons less carbon storage by 2050 than if demand had been constant).

Figure 4 illustrates the relative harvest levels of PPW and PST under each scenario through 2050. We note that pine sawtimber harvests are relatively constant across all scenarios, but that the “CONST-CARB” and “SHIFT-BASE” scenarios provide greater levels of PST harvests by the end of the projection horizon than the “SHIFT-CARB” scenario. This result follows from the capacity for both carbon offset markets and falling PPW demand to raise inventory of PST in later years but when both are acting on the PPW market, it can lead to greater PST harvests initially, drawing down inventory of PST and eventually limiting harvests of PST.

*Figure 4: Projected percentage difference in southwide harvest of pine roundwood under a forest carbon offset market relative to no carbon offset markets (southern U.S.)*




In Figure 5, we show the projected levels of aboveground carbon storage and annual carbon sequestration under each scenario. Relative to the baseline scenario ("CONST-BASE"), we see that all scenarios provide greater levels of aboveground storage through 2030 but the "SHIFT-CARB" scenario leads to less storage by 2050 than the baseline scenario. This illustrates how falling PPW demand coupled with bidding pressure from offset markets can lower overall carbon storage as pine plantation acreage is converted from a forested use to a non-forested use (see Figure 6). Figure 5 shows that the absence of carbon offset market activity in this case leads to greater overall carbon storage and higher rates of annual sequestration in a market with falling demand for PPW. We not that the largest levels of carbon storage and annual rates of sequestration are achievable with when offset market activity is deferring PPW harvests but when the demand for PPW is constant and not declining.

***Figure 5: Southwide aboveground carbon storage and annual sequestration relative to baseline scenario***

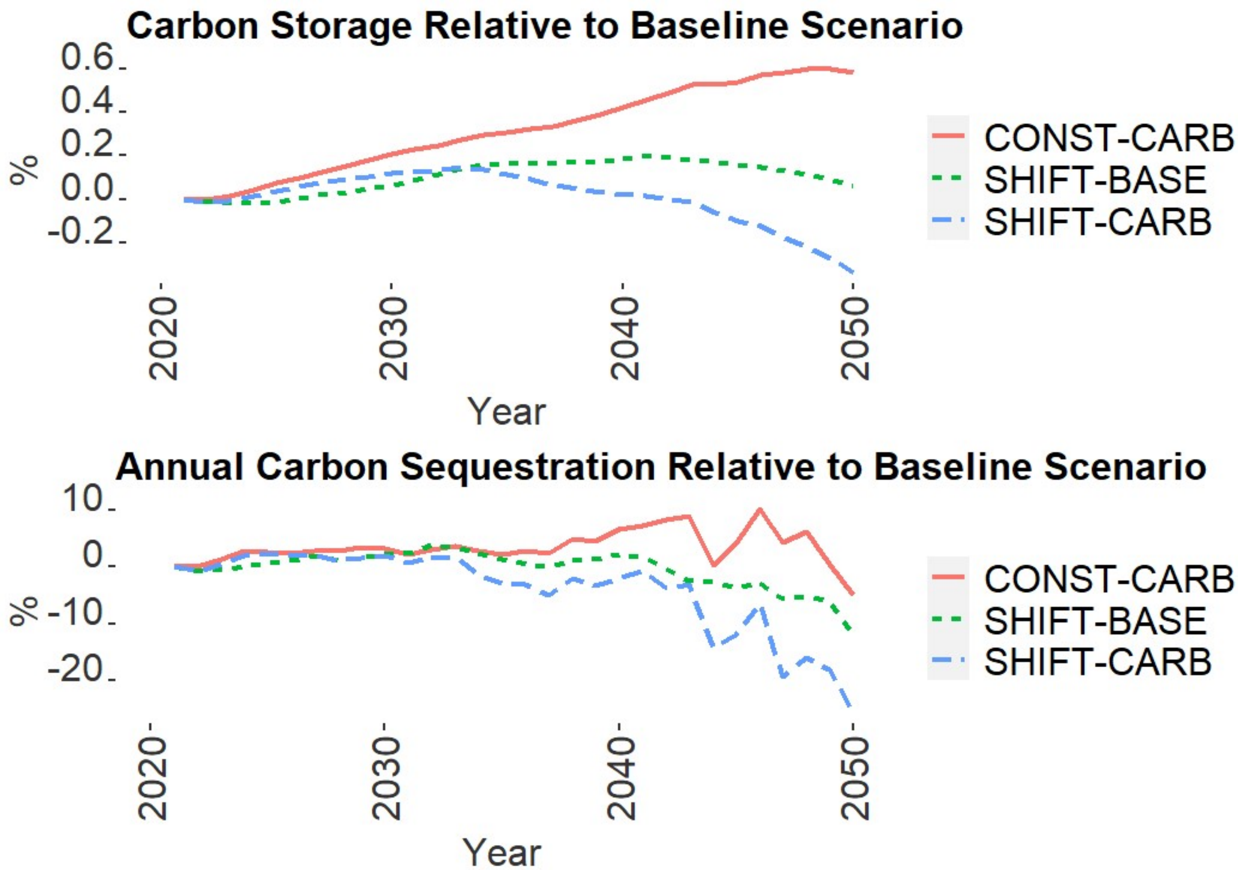
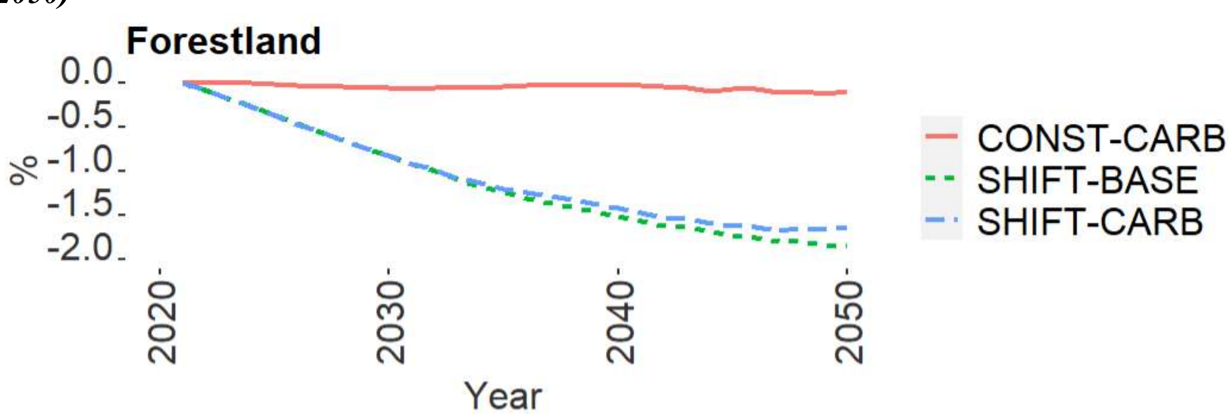



***Figure 6: Percentage of southern region in a forested use relative to baseline scenario (2020-2050)+++***




+++***Non-forested land uses include residential or urban development and agricultural land.***

Short-term market projections provide us with an illustration of how consistent undershooting of the market equilibrium in the pulpwood market can undermine the efficacy of forest carbon offsets at achieving additionality when the demand for pulpwood is falling. In Table 2, we list the percent of PPW harvests, PST harvests, carbon storage, and annual sequestration above or below the baseline scenario. In Table 3, we list the percentage of projected harvests that fall above or below the market equilibrium: $100 * \ln\left(\frac{\sum_i \sum_o H^*_{iojt}}{\sum_i \sum_o Q^*_{iojt}}\right)$ .

The data in Table 2 shows that annual carbon sequestration in the southern region is increasing from 2022 to 2030, but lower in the "SHIFT-CARB" scenario than it is under the "CONST-CARB" scenario. At the same time, we can see in Table 3 that PPW harvests deviate further from the market equilibrium when offsets are active. We note that PPW is under-harvested relative to the market equilibrium by 3.2% in 2022 and by as much as 7.2% by 2030 when demand is flat ("CONST-CARB"). This scenario also displays the highest levels of carbon storage and the highest rates of annual sequestration (see Figure 5). However, when PPW demand is falling at a rate of 3% per year, PPW is under-harvested by only 1.4% in 2022 and actually over-harvests relative to the market solution by 3.3% in 2030. When projected PPW harvests overshoot the market solution with an active offset market (as in 2030 under the "SHIFT-CARB" scenario), this indicates that offset demand was not large enough to bid up pulpwood prices to defer any additional carbon beyond the amount deferred naturally by the industrial roundwood markets. This is also true for the scenarios where offset market activity is not active ("CONST-BASE" and "SHIFT-BASE"), where we see PPW harvest slightly exceeds the market equilibrium. In general, the model projects that PPW harvests will be closer to the market equilibrium solution under the "SHIFT-CARB" scenario than under the "CONST-

CARB" scenario (see Figure 7), since falling demand for PPW achieves as much the effect of harvest deferrals without the aid of an offset market. At most only 150,000 MCF of pulpwood harvest is deferred per year when pulpwood demand is falling, but as much as 350,000 MCF of pulpwood is deferred per year when pulpwood demand is held constant at 2728 MMCF per year.

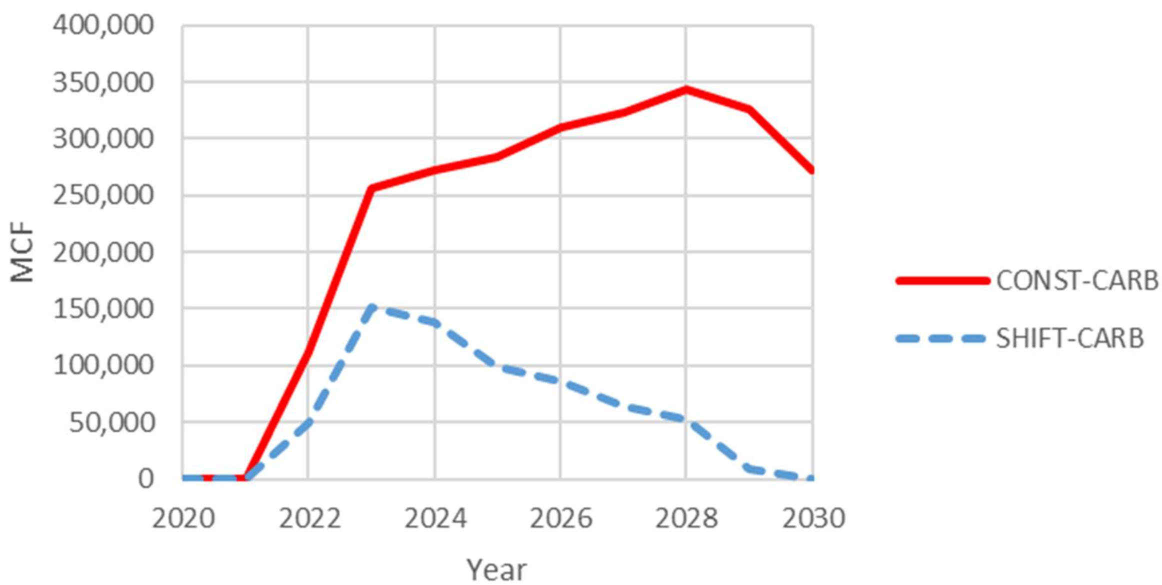
***Table 2: Projected harvest and carbon storage in the southern region under alternative scenarios relative to Baseline scenario ("CONST-BASE")***

| | 2022 | 2024 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|
| **PPW Harvest** | | | | | |
| CONST-CARB | 0.0% | +0.2% | +0.4% | +0.7% | +0.8% |
| SHIFT-BASE | -2.1% | -4.2% | -6.2% | -8.0% | -9.8% |
| SHIFT-CARB | -2.1% | -4.1% | -5.9% | -7.8% | -9.6% |
| **PST Harvest** | | | | | |
| CONST-CARB | 0.0% | 0.0% | +0.1% | +0.1% | +0.2% |
| SHIFT-BASE | 0.0% | 0.0% | +0.1% | +0.1% | +0.2% |
| SHIFT-CARB | 0.0% | 0.0% | +0.1% | +0.2% | +0.3% |
| **Carbon Storage** | | | | | |
| CONST-CARB | 0.0% | +0.1% | +0.1% | +0.2% | +0.2% |
| SHIFT-BASE | 0.0% | 0.0% | 0.0% | 0.0% | +0.1% |
| SHIFT-CARB | 0.0% | 0.0% | +0.1% | +0.1% | +0.1% |
| **Sequestration** | | | | | |
| CONST-CARB | 0.0% | +2.8% | +2.4% | +2.7% | +3.3% |
| SHIFT-BASE | -0.1% | 0.0% | +1.1% | +1.1% | +2.2% |
| SHIFT-CARB | -0.1% | +2.0% | +1.9% | +1.1% | +1.9% |

***Table 3: Percent of harvest above or below the southwide equilibrium under 4 scenarios (a measure of disequilibrium in the industrial roundwood markets)***

| | 2022 | 2024 | 2026 | 2028 | 2030 |
|---|---|---|---|---|---|
| **PPW Harvest** | | | | | |
| CONST-BASE | +0.2% | +0.2% | +0.2% | +0.4% | +0.9% |
| CONST-CARB | -3.2% | -7.5% | -8.4% | -9.2% | -7.2% |
| SHIFT-BASE | +0.2% | +0.2% | +0.5% | +1.1% | +2.1% |
| SHIFT-CARB | -1.4% | -4.0% | -2.5% | -1.5% | +3.3% |
| **PST Harvest** | | | | | |
| CONST-BASE | +1.5% | +2.2% | +3.2% | +4.8% | +6.4% |
| CONST-CARB | +1.2% | +1.8% | +2.8% | +4.2% | +5.4% |
| SHIFT-BASE | +1.5% | +2.1% | +3.0% | +4.5% | +6.0% |
| SHIFT-CARB | +1.2% | +1.8% | +2.7% | +4.1% | +5.4% |

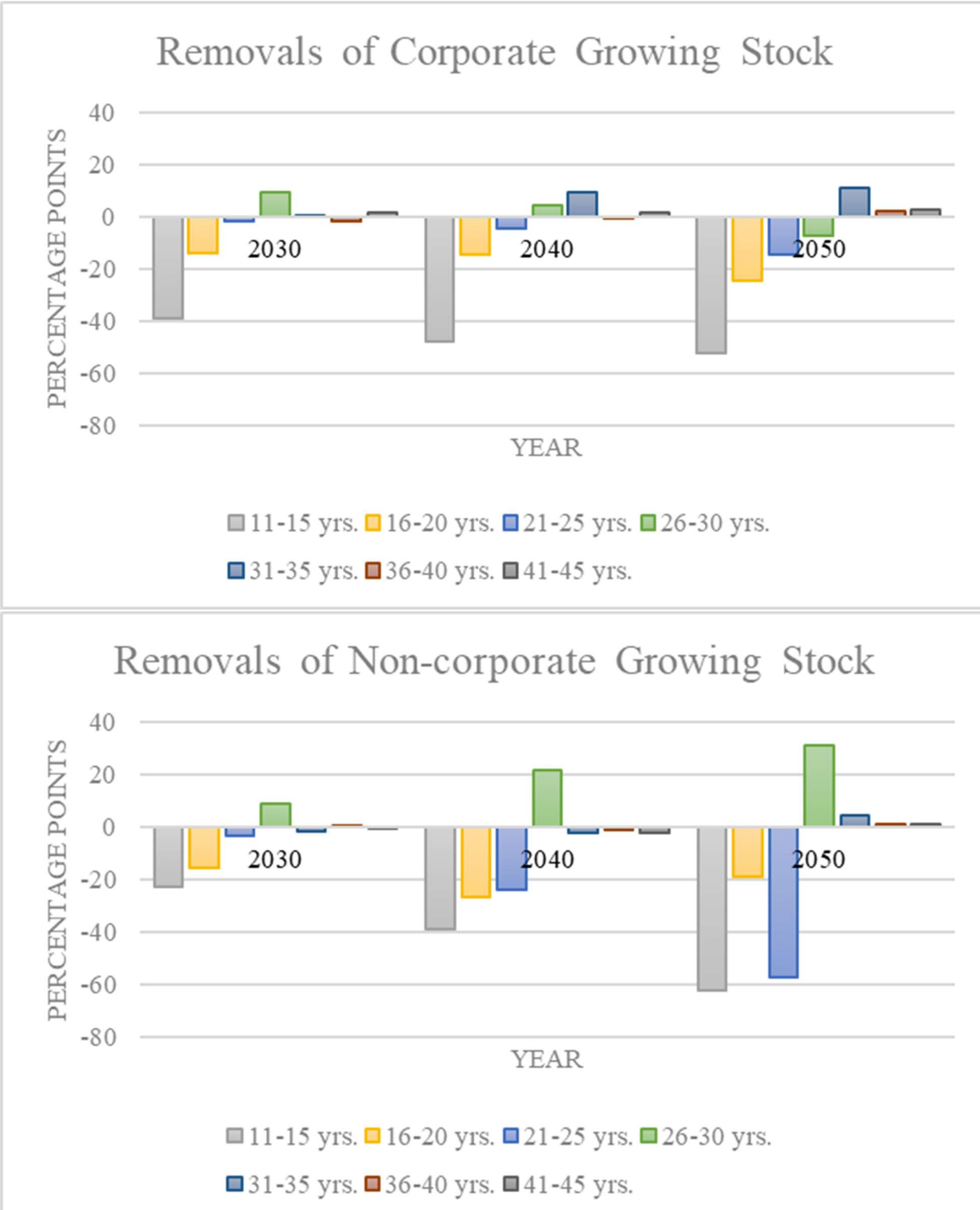
***Figure 7: Volume of pulpwood harvest deferred under a forest carbon offset program with constant and shifting demand scenarios (2020-2030)***




In Figure 8, we illustrate the effects of forest carbon offset market activity on the harvest of pine plantation growing stock across age classes. The effects of offset market activity on inventory volume are expressed in percentage terms and difference in these effects across the constant demand scenario and the shifted demand scenario are presented.[3] For example, we see from Figure 8 that in 2030 there is a projected 40 percentage point *decrease* in the corporate harvest of pine plantations in the 11-15 year age class due to the introduction of carbon offsets as demand for PPW increases from its trajectory toward 2012 MMCF in 2030 to a constant 2729 MMCF per year. This change is only around 20 a percentage point decrease in 2030 for non-corporate lands. In contrast, we see a 10 percentage point *increase* in the effects of carbon offset markets on the harvest of both corporate and non-corporate pine plantations in the 26-30 year age class in 2030. This displays the capacity for larger levels of PPW demand to delay harvests. Removals of pine plantations younger than 26 years in age are less preferred than removals of plantations older than 26 years as forest carbon offset markets are introduced under circumstances of larger annual demand for PPW. In general, we see that higher demand for PPW decreases removals of pine plantations in the younger age classes, especially as the projection horizon extends through 2050. This chart shows the effectiveness of forest carbon offsets in deferring harvests and generating additionality in younger forests wen there is a larger demand for pulpwood.

[3] This difference in percentage differences can be written for each age class within an ownership group as: $\Delta = 100 * \left( \ln\left( \frac{\sum_i H_{igm,PPW}^{CONST-CARB}}{\sum_i H_{igm,PPW}^{CONST-BASE}} \right) - \ln\left( \frac{\sum_i H_{igm,PPW}^{SHIFT-CARB}}{\sum_i H_{igm,PPW}^{SHIFT-BASE}} \right) \right)$.

***Figure 8: Projected percentage point difference in the effects of carbon offset markets on removals pine plantation growing stock by age class across constant and falling PPW demand scenarios***



## 5. Discussion

The sensitivity of our projections to changes in demand scenarios provide important context for how changing harvest patterns can impact the temporal distribution of carbon sequestration and undermine the effectiveness of forest carbon offset markets at achieving additionality. We have specified the introduction of forest carbon offset markets as a new source of demand which raises the bid price for pulpwood material *after* the market equilibrium is determined by participants in the industrial pulpwood market. This is represented in our projection model by re-defining the relative importance of meeting the market solution when determining harvest across age classes, forest types, sub-regions, and ownership groups. When forest carbon offset markets consistently undershoot the market equilibrium, our model shows how removal patterns across age classes can change and how falling demand for industrial uses of the PPW growing stock can limit the potential for carbon offsets to defer harvest activity to older stages of forest growth.

Our results also demonstrate how a greater emphasis on meeting the market equilibrium for a larger quantity of pine sawtimber can further reduce demand for pulpwood-sized logs under a given cull factor (we have assumed here that 30% of the volume of pine logs greater than 9" DBH can be utilized as pulpwood). If pine sawtimber harvests are not allowed to deviate from the market equilibrium, there will be a greater volume of culled wood available to meet the demand for pine pulpwood, thereby further contributing to a displacement of the equilibrium in the industrial pine pulpwood market. When coupled with low levels of pulpwood demand, both the cull of larger-diameter sawtimber and a de-emphasis on meeting the equilibrium in the pine pulpwood market contributes to a market where additional carbon storage may be constrained.

Our framework is subject to several limitations. First, our illustration of the market dynamics in this setting requires an assumption about the pathway of future demand. We have kept our scenarios relatively simple to demonstrate the effects of forest carbon offsets under consistently unexpected declines the demand for pine pulpwood across the U.S. south. Future research utilizing this projection framework for building a short-term understanding of additionality could specify demand trajectories for smaller wood baskets with known increases in nearby mill capacity. A second limitation related to the manner in which forest carbon offsets are represented in the SRTS model. We have related offset market activity to the relative importance of meeting the market equilibrium in the market for pulpwood. When this target is specified to be less important than the target that specifies the market solution for larger-diameter roundwood, we see that there is an excess supply of industrial uses of pulpwood and this excess supply represents the deferred harvest of pulpwood re-purposed for carbon sequestration. The magnitude of the change in this relative importance on this target weights is a matter of analyst subjectivity. A more thorough analysis would be to vary this size of the relative importance of meeting the PST market equilibrium over the PPW market equilibrium and tracking the degree of harvest deferrals and annual sequestration across many projections. This larger set of scenarios would provide a range of possible outcomes that can be used to better understand the likely impact of offset programs that defer harvest when there are competing demands for logs in the industrial roundwood market.

A third limitation is that we have only considered here the impact of offset markets on the market for pine pulpwood and assumed that offset programs do not directly relate to deferrals of larger-sized roundwood. A more thorough sensitivity analysis would consider the potential for offset markets to defer the harvest of pine sawtimber via shifts in the relative importance of meeting the market equilibrium under falling, flat, or rising demand. A fourth limitation relates to the temporal impact of forest carbon offsets. It could be the case that forest carbon offsets initially undershoot the market equilibrium for a roundwood product but then begin to generate no additional demand in later years of the projection. Alternatively, it may be well into the future after forest inventory and age class distributions have evolved before offset markets generate similar distortions in industrial roundwood markets. Future research may seek to explore temporal variation in the new sources of demand generated by forest carbon offsets.

Our results have important implications for forest carbon offset protocol design, but we note that the challenges in achieving additionality are not unique to voluntary offset programs. Government provision of forest carbon sequestration through similar mechanisms face similar challenges of determining additionality of offsets with uncertain demand or shifting demand. This paper shows how a continuation of recent trends favoring sawtimber removals over pulpwood (which corresponds to a positive shift in harvest likelihood relative to stand age) will shift the composition of likely additional offset credits in the future. We also show how the variation in age class profiles varies over time as forest inventories evolve. If offset markets continually undershoot the market clearing solution in the industrial pulpwood market, this age class distribution can also change, leading to a difference in efficacy of offset credits over time. Given rapidly changing market dynamics in the US forest sector and the relative fungibility of forest harvests to different product pools, we argue that forward-looking metrics based on empirically grounded structural market models provide a proxy for harvest likelihood that factors in changing market conditions, including demand-side dynamics.

## References


Abt, R., F. Cubbage, K. Abt. 2009. Projecting southern timber supply for multiple products by subregion. *Forest Products Journal* 59(7/8): 7-16.

Austin, K., J. Baker, B. Sohngen, C. Wade, A. Daigneault, S. Ohrel, S. Ragnauth, A. Bean. 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. *Nature Communications* 11: 5946.

Baker, J. S., Proville, J., Latane, A., Aramayo, L., Parkhurst, R. (2020). Additionality and Avoiding Grassland Conversion in the Prairie Pothole Region of the United States. *Rangeland Ecology and Management.* 73(2): 201-215.

Burrill, E.A., A.M. DiTommaso, J.A. Turner, S.A. Pugh, G. Christensen, C.J. Perry, B.L. Conkling. 2021. The Forest Inventory and Analysis Database: Database Description and User Guide for Phase 2 (version: 9.0.1). U.S. Department of Agriculture, Forest Service. 1026p. Available at web address: http://www.fia.fs.fed.us/library/database-documentation/. Last accessed: Apr. 5, 2021.

Coulston, J., J. Westfall, D. Wear, C. Edgar, S. Prisley, T. Treiman, R. Abt, W. Brad Smith. 2018. Annual Monitoring of US Timber Production: Rationale and Design. *Forest Science* 64(3): 533-543.

Daigneault, A., C. Johnston, A. Korosuo, J. Baker, N. Forsell, J. Prestemon, R. Abt. 2019. Developing Detailed Shared Socioeconomic Pathway (SSP) Narratives for the Global Forest Sector. *Journal of Forest Economics* 34: 7-45.

Foley, T. 2009. Extending Forest Rotation Age for Carbon Sequestration: A Cross-Protocol Comparison of Carbon Offsets of North American Forests. *Master's Thesis*. Nicholas School of the Environment, Duke University. Durham, NC.

Ignizio, J. 1985. Introduction to Linear Goal Programming. Sage Publications. Newbury Park, CA.

Kornbluth, J. 1973. A Survey of Goal Programming. *OMEGA: The International Journal of Management Science* 1(2): 193-205.

Mason, C. F., & Plantinga, A. J. (2013). The additionality problem with offsets: Optimal contracts for carbon sequestration in forests. *Journal of Environmental Economics and Management*, 66(1): 1-14.

Miranda, M., P. Fackler. 2002. Applied Computational Economics and Finance. MIT Press. Cambridge, MA.

Murray, B.C., B. Sohngen, M.T. Ross. 2007. Economic consequences of consideration of permanence, leakage and additionality for soil carbon sequestration projects. *Climatic Change* 80: 127-143.

Nagubadi, R.V., Zhang, D. 2005. Determinants of Timberland Use by Ownership and Forest Type in Alabama and Georgia. *Journal of Agricultural and Applied Economics* 37(1): 173-186.

Prestemon, J.P., Wear, D.N. 2000. Linking Harvest Choices to Timber Supply. *Forest Science* 46(3): 377-389.

Tahvonen, O., Rautiainen, A. 2017. Economics of forest carbon storage and the additionality principle. *Resource and Energy Economics* 50: 124-143.

Zhao, J., Daigneault, A., & Weiskittel, A. (2020). Forest landowner harvest decisions in a new era of conservation stewardship and changing markets in Maine, USA. *Forest Policy and Economics* 118: 102251.