A Range of Management Strategies for Planted Pine Systems Yields Net Climate Benefits

Sarah J. Puls[1], Rachel L. Cook[1], Justin S. Baker[1], James L. Rakestraw[2]

[1] Department of Forestry and Environmental Resources, North Carolina State University,
Raleigh, NC 27695, USA
[2] International Paper, Statesboro, GA 30458, USA

Abstract

Managed forests, including plantation systems, play a vital and often underappreciated role in contributing to the global carbon sink and mitigating climate change, and determining the most effective mitigation strategies requires accounting methods that accurately assess the climate effects of forests. We use a dynamic life cycle assessment methodology to compare the climate effects of thirty-six forest management scenarios with varying rotation lengths for loblolly pine plantations in the southern U.S., including both *in situ* and *ex situ* greenhouse gas fluxes. We also evaluate the effectiveness of using only carbon stock estimates to assess the net climate effect of a given management strategy relative to radiative forcing metrics. Using carbon stocks as the metric, we failed to attribute management strategies with higher relative climate benefits, emphasizing the need for greenhouse gas accounting methodologies that directly represent the effect of forest management on potential atmospheric warming mitigation efforts. When radiative forcing is used for comparison, our results show that management decisions such as thinning and rotation length should be adjusted based on stand-specific conditions, and that overgeneralized strategies, such as extending rotation lengths, lowered or had little effect on climate benefits for many scenarios.

Introduction

From 2011-2020, global temperatures were 1.1°C above the pre-industrial average, and 3.3 to 3.6 billion people are now estimated to be vulnerable to the effects of climate change (1). The forest sector plays an important role in global greenhouse gas (GHG) fluxes and can contribute to climate change mitigation by sequestering carbon from the atmosphere, storing carbon temporarily or permanently in the form of biomass and harvested wood products (HWPs), and providing low-emission materials for energy, construction, and other uses (2–4).

Managed loblolly pine (*Pinus taeda* L.) plantations in the southern U.S., in particular, offer a unique and likely underappreciated opportunity for climate change mitigation because of their prevalence and productivity within the southern U.S. forest landscape (5). While annual carbon sequestration rates in many parts of the U.S. have decreased in recent years, the U.S. forest sector sink has remained stable (6), in part due to increasing carbon sequestration rates in the southern U.S. that have co-occurred with plantation investments, productivity improvement, and increased timber production. Tian et al. (7) showed that continued investment in pine plantations would help support and enhance the U.S. forest carbon sink over time. Loblolly pine plantations are often intensively managed, and interventions such as fertilization (8) and rotational strategies (9) can improve forest and HWP carbon outcomes over time. However, the relationship between carbon sequestration and management choices is complex (10). Planted pine systems may also require energy and emissions-intensive inputs, which can affect the net climate benefits of these systems. Thus, the realization of potential climate benefits from loblolly pine plantations requires a nuanced analysis of the effects of management (*i.e.*, silviculture) on carbon sequestration and net GHG fluxes.

Historically, studies that assess the climate change mitigation potential of management practices on loblolly pine plantations have used carbon stocks or carbon accumulation (*i.e.*, sequestration) as a proxy for climate effects (8,9,11–13). Although these metrics are relatively easy to measure and model, they do not capture the full climate effects of a forest system. For example, fossil fuels are emitted in both forest management and HWP production operations (14–16), and some HWP carbon may be emitted to the atmosphere as methane (CH_4) if decay occurs in anaerobic landfill conditions (17). When only carbon sequestration or stocks are considered, the effects of non-biogenic and non-CO_2 GHG fluxes will not be accounted for.

Numerous methodologies have been developed to account for non-biogenic and non-CO_2 GHG fluxes. Possibly the most prominent is the global warming potential (GWP), which represents the cumulative radiative forcing effect of a pulse of GHG relative to the equivalent effect for CO_2 over a given time horizon, typically 100 years (18). GWP has been increasingly criticized for its lack of consideration for temporal effects of GHG emissions. It is highly sensitive to the chosen time horizon, giving less weight to shorter-lived GHGs when longer time horizons are used. GWP expresses the effects of the GHG emission over the entire GWP time horizon, regardless of the time period of the study for which the metric is being used. Finally, GWP does not allow accounting for temporary carbon storage, such as in HWPs (19,20). The value of temporary carbon storage is highly debated (21–23). Some studies have found that temporarily reducing atmospheric GHG concentrations actually leads to higher concentrations once the carbon is released than if it were never removed (21,22). Other studies point to benefits of temporary storage, including delayed or reduced warming effects that give ecosystems more time to adapt and society more time to implement mitigation technologies and policies (23–25). Accounting methodologies that can appropriately quantify both cumulative GHG emissions and the amount and duration of carbon stored temporarily are needed (26). One such approach is the dynamic life cycle assessment (dynamic LCA) approach, proposed by Levasseur et al. (19), in which emissions are accounted for in the year in which they occur, and the radiative forcing effects are calculated for subsequent years based on the lifetimes of the individual pulses of GHGs.

In this study, we adapt the dynamic LCA approach to evaluate the radiative forcing effects of site quality and forest management across a forest landscape, while considering the timing of forest sector sequestration and emissions. Our objectives are to 1) quantify the biogenic and non-biogenic sequestration and emission pulses associated with loblolly pine plantations in the southern U.S. for various management regimes, 2) identify the regimes that offer the most climate benefits for a given site quality based on the radiative forcing effects, and 3) determine if there are any differences in the identified beneficial regimes by comparing net radiative forcing and carbon stocks as the performance metric of interest.

Methods

Scenarios

We compared GHG fluxes from thirty-six management scenarios over a time horizon of 100 years. The scenarios represented all combinations of three site indices, three planting densities, two thinning schemes, and two mid-rotation fertilization schemes (Table 2). Each scenario was tested with rotation lengths from 18 to 40 years, such that the same rotation length was repeated as many times as possible within the time horizon. We refer to each scenario and rotation length combination as a management regime. All scenarios used improved genetics. Stands were assumed to be located in the coastal plain physiographic region of the southern U.S. at coordinates 31.9°N and 81.7°W. All stands received chemical site preparation, were bedded at planting, and received

22 kg ha^{-1} (20 lb ac^{-1}) of phosphorus fertilizer at establishment. Thins were conducted in the first year in which the stand basal area was at least 27 m^{2} ha^{-1} (120 ft^{2} ac^{-1}) and the dominant height was at least 12 m (40 ft) as is operationally typical in the region. Stands were thinned down to 16 m^{2} ha^{-1} (70 ft^{2} ac^{-1}). Fertilization was applied the year after thinning and included 224 kg ha^{-1} (200 lb ac^{-1}) of nitrogen and 28 kg ha^{-1} (25 lb ac^{-1}) of phosphorus. For scenarios with fertilization but no thinning, the fertilization age from the corresponding scenario with a thin was used. All scenarios had a one year period between harvest and planting in which site preparation activities were assumed to take place (27).

Table 2. Conditions for thirty-six modeled forest management scenarios for loblolly pine plantations in the southern U.S.

Scenario number	Site index (m)	Planting density (TPH)	Thinning Regime	Fertilization Regime
S1	20	988	Thin, age 15	Fertilization, age 16
S2	20	1359	Thin, age 14	Fertilization, age 15
S3	20	1730	Thin, age 14	Fertilization, age 15
S4	23	988	Thin, age 13	Fertilization, age 14
S5	23	1359	Thin, age 12	Fertilization, age 13
S6	23	1730	Thin, age 11	Fertilization, age 12
S7	26	988	Thin, age 11	Fertilization, age 12
S8	26	1359	Thin, age 10	Fertilization, age 11
S9	26	1730	Thin, age 9	Fertilization, age 10
S10	20	988	Thin, age 15	No fertilization
S11	20	1359	Thin, age 14	No fertilization
S12	20	1730	Thin, age 14	No fertilization
S13	23	988	Thin, age 13	No fertilization
S14	23	1359	Thin, age 12	No fertilization
S15	23	1730	Thin, age 11	No fertilization
S16	26	988	Thin, age 11	No fertilization
S17	26	1359	Thin, age 10	No fertilization
S18	26	1730	Thin, age 9	No fertilization
S19	20	988	No thin	Fertilization, age 16
S20	20	1359	No thin	Fertilization, age 15
S21	20	1730	No thin	Fertilization, age 15
S22	23	988	No thin	Fertilization, age 14
S23	23	1359	No thin	Fertilization, age 13
S24	23	1730	No thin	Fertilization, age 12
S25	26	988	No thin	Fertilization, age 12
S26	26	1359	No thin	Fertilization, age 11
S27	26	1730	No thin	Fertilization, age 10
S28	20	988	No thin	No fertilization

S29	20	1359	No thin	No fertilization
S30	20	1730	No thin	No fertilization
S31	23	988	No thin	No fertilization
S32	23	1359	No thin	No fertilization
S33	23	1730	No thin	No fertilization
S34	26	988	No thin	No fertilization
S35	26	1359	No thin	No fertilization
S36	26	1730	No thin	No fertilization

Site index is for base age 25; site index values are rounded for brevity and represent 65, 75, and 85 ft, respectively; TPH = trees per hectare at planting.

Scope

In situ carbon pools

For each regime, biomass and harvested timber outputs were modeled using the NC State University-Virginia Tech Forest Productivity Cooperative's FASTLOB 3.1 growth and yield model (28,29). Biomass (*i.e.*, dry weight) outputs were converted to carbon stocks using a coefficient of 0.5 tC (t biomass)$^{-1}$ for all pools. The modeled, *in situ* carbon pools included crop tree stems, branches, foliage, coarse roots, fine roots, and coarse woody debris (CWD). Soil and forest floor GHG fluxes not from these pools were assumed to be constant between scenarios and were therefore not considered (30–32). Because FASTLOB does not provide biomass data for stand ages 1-5, biomass for these ages was estimated by assuming linear growth up to the data point given for age 6. Carbon stocks in decaying roots and branches from harvested trees are calculated according to decay functions by Ludovici et al. (33) (equation 1) and Radtke et al. (34) (equation 2), respectively.

$$CR_{roots} = CH_{roots} * e^{-0.0534*t} \tag{1}$$

$$CR_{CWD} = CH_{CWD} * \left(\frac{longitude}{latitude}\right)^{-0.1247t} \tag{2}$$

where CH_{pool} is the carbon in the pool when the tree was harvested, and CR_{pool} is the carbon remaining in the pool t years after harvest.

Fossil fuel emissions from silviculture are calculated independently from the FASTLOB model using the rates listed in Table 3. These include upstream emissions from the production of loblolly seedlings, chemical herbicide, nitrogen fertilizer, and phosphorus fertilizer, as well as emissions from bedding, application of herbicide and mid-rotation fertilizer, and harvesting. Upstream emissions were assumed to take place within the same year in which the product was used. Thinning was assumed to have similar associated emissions per hectare to the final harvest (14). N_2O emissions from the denitrification of nitrogen fertilizer were also estimated.

Table 3. Emission factors used to calculate GHG emissions from silviculture

Emission Source	Emission Factor	Unit
Upstream N fertilizer production (14)	0.00542	tCO_2 / kg N
Upstream P fertilizer production (14)	0.00553	tCO_2 / kg P
Upstream seedling production (35–37)	2.2E-05	tCO_2 / seedling
Upstream herbicide production (14)	0.02094	tCO_2 / kg herbicide
Herbicide application (14)	0.02202	tCO_2 / ha
Bedding (14)	0.14305	tCO_2 / ha
Fertilizer application (14)	0.02202	tCO_2 / ha
N denitrification (38)	1.57E-05	tN_2O / kg N
Harvest (14)	0.58692	tCO_2 / ha

Ex situ carbon pools

HWP carbon stocks, biogenic emissions from HWPs, and fossil fuel emissions from production were modeled using the Loblolly Wood Inventory, Storage, and Emissions (LobWISE 1.1) model, developed by Puls et al. (12), for each set of harvested timber outputs. Harvested timber outputs were sorted into log types and secondary products according to the regional default parameters in LobWISE. Biogenic CO_2 emissions result from mill residue and energy products (*e.g.*, wood pellets) that are burned, other products that transition out of use and are burned or decay, and products that decay in landfills. Biogenic CH_4 emissions result only from products that decay in landfills. Fossil fuel emissions from production result from the transportation of harvested timber from the harvest site to the mill and all fossil fuel emissions associated with the manufacturing of the primary product at the mill. Except for burned mill residue and energy products from the modeled forest stand, biogenic emissions from HWP production are not included. Fossil fuel emissions from later life stages, such as transportation to the sale or use site, manufacturing or construction into secondary products, recycling processes, transportation to the disposal site, and disposal processes are excluded.

Displacement factors that represent the climate benefits of using wood for energy and construction materials rather than using products with higher associated emissions, such as fossil fuels and concrete, are sometimes used in studies assessing climate effects of forest management (39–41). However, estimates of appropriate displacement factors range considerably in the literature (42), and some studies suggest that inconsistency in the approaches used to calculate displacement factors, as well as reliance on economic and technological assumptions that are not supported by the literature, has led to overestimation of the benefits of wood product substitution (43–45). Therefore, we do not include potential benefits of substitution in our analysis, so our results will likely underestimate forest climate benefits.

Dynamic LCA calculations

Net radiative forcing

We use the dynamic LCA methodology proposed by Levasseur et al. (19) to calculate the radiative forcing effect ($RF_{s,y}$) of all emissions or sequestration within the system boundaries at any year, y, within the time horizon for a source, s. First, the impulse response function ($IRF(t)$), which describes the portion of a unit of GHG released to the atmosphere in year i that remains in the atmosphere t years since release, is calculated for each GHG included in the study according to IPCC guidance (46,47). We include CO_2 (equation 3), CH_4, and N_2O emissions (equation 4), and thus, three impulse response functions are calculated:

$$IRF_{CO_2}(t) = a_0 + \sum_k a_k e^{-t/\tau_k} \tag{3}$$

$a_0 = 0.2173$; $a_1 = 0.224$; $a_2 = 0.2824$; $a_3 = 0.2763$; $\tau_1 = 394.4$ years; $\tau_2 = 36.54$ years;

$\tau_3 = 4.304$ years

$$IRF_{GHG}(t) = e^{-t/\tau_{GHG}} \tag{4}$$

$\tau_{CH4} = 12.4$; $\tau_{N2O} = 121$

Next, the *IRF(t)* is multiplied by the radiative efficiency (RE_{GHG}) for the respective GHG and by the initial amount of GHG released in year i ($GHG_{s,i}$) for each subsequent year to calculate the radiative forcing effect of $GHG_{s,i}$ in year t (equation 5).

$$RF_{s,i}(t) = GHG_{s,i} * IRF_{GHG}(t) * RE_{GHG} \tag{5}$$

Finally, for each year, y, $RF_{s,y}$ is the sum of all $RF_{s,i}(t)$ for which $(i + t) = y$. In other words, $RF_{s,y}$ is the current radiative forcing effect in year y of all previous emission or sequestration pulses within the system boundaries for a given source (equation 6).

$$RF_{s,y} = \sum_{i=1}^{y} RF_{s,i}(t) * \delta_{i+t,y} \tag{6}$$

Sources of emissions and sequestration in our study are CO_2 emissions from forest decay, which includes decay of foliage, CWD, and roots, CO_2 emissions from HWPs, CH_4 emissions from HWPs, fossil fuel emissions from production, fossil fuel emissions from silviculture, N_2O emissions from fertilizer, and forest sequestration. Emissions from forest decay and forest sequestration for year i are defined as the difference between the carbon stocks in tC, C, in year $i-1$ and year i (equation 7).

$$GHG_{for\ dec/seq,i} = (C_{i-1} - C_i) * \frac{44}{12} \tag{7}$$

Sequestration is thus treated as a negative emission, because it reduces the amount of atmospheric CO_2 and therefore has cooling effects on the atmosphere compared to a scenario in which the sequestration does not take place (20). Carbon that moves from one pool to another is not considered to be emitted or sequestered, as it is merely continuing to be stored and has the same effect on the atmosphere regardless of the pool in which it is stored. For trees that are harvested, stem carbon is assumed to move to the HWP pool and branch carbon is assumed to move to the CWD pool. Root and CWD carbon then decay according to equations 1 and 2, respectively. All foliage from harvested trees is assumed to decay in the year of harvest.

To analyze the climate impact of each regime, we then calculate the net radiative forcing across all sources for year y (equation 8), and an average annual net radiative forcing across the time horizon, *TH* (equation 9), such that positive and negative radiative forcing effects of equal magnitude that occur in the same year are canceled out.

$$netRF_y = \sum_s RF_{s,y} \tag{8}$$

$$netRF_{avg} = \frac{1}{TH}\left(\int_{y=1}^{TH} netRF_y dy\right) \tag{9}$$

Calculations not executed in FASTLOB 3.1 and LobWISE 1.1 were performed in the programming software, Python 3.11.1.

Carbon stocks

Carbon stocks are often used as a proxy for climate benefits in forest management studies, carbon offset projects, and forest carbon policy (12,48,49). To compare the effect of the metric used (*i.e.*, net radiative forcing v. carbon stocks) on the results, we calculate a metric similar to $netRF_{avg}$ for carbon stocks. C_{avg} can be defined as the average carbon stock each year in *in situ* and *ex situ* pools across the time horizon (equation 10).

$$C_{avg} = \frac{1}{TH}\left(\int_{y=1}^{TH} C_y dy\right) \tag{10}$$

where C_y is the carbon stock in year y.

Landscape approach

In LCA studies involving wood products, the dynamic LCA methodology presents a so-called “chicken or egg” dilemma, in which practitioners must choose to associate the product with forest growth before or after its production. In a “before” scenario (*i.e.*, the “egg”), the trees are planted in years prior to the product lifetime and harvested for the purpose of making the product. In an “after” scenario (*i.e.*, the “chicken”), trees are replanted to take the place of the trees harvested to make the product and grow as the product is used and discarded. Because dynamic LCA accounts for the timing of emissions and sequestration, the choice of this temporal boundary for sequestration greatly affects the estimated global warming impact of the product (20,50).

In our study, although the focus is not on any individual wood product, our results would be similarly biased based on the choice of a temporal boundary. For example, if all scenarios began at planting, sequestration would occur for many years before emissions, and emissions would start sooner in shorter rotations. This starting point would make all scenarios appear as though they were a significant carbon sink and as though shorter rotations resulted in more emissions than longer rotations, based primarily on the choice of timing rather than on the effects of forest management. In reality, forests of many age classes exist across the landscape at any given point in time, and policies, carbon projects, and management changes that affect the climate benefits of the forest may take place at any age class or even across several age classes. Our goal, therefore, is to assess the climate effects of different management for a forest landscape level, rather than for an individual forest stand. A forest landscape can be defined as “a forest estate with equal areas of each age class” (51). In a landscape approach to forest and forest product carbon modeling, it is assumed that the biomass grown in any year is approximately equal to the biomass harvested (52).

To apply this landscape approach to our study, for each regime, we conduct the analysis described above for 1000 representative stands, each 0.405 ha (1 ac) in size, which have an approximately uniform age class distribution that is maintained throughout the time horizon. The metrics described above are calculated for all 1000 stands simultaneously, such that they represent the climate effects (*e.g.*, $netRF_{avg}$) or carbon stocks (C_{avg}) when a regime is applied consistently across the landscape for the duration of the study time horizon. For stands that are not age 0 in year 0 of the time horizon, it is assumed that the regime has been applied to that stand since its planting. Only carbon from stands harvested in or after year 0 is included in the study. In other words, carbon in roots and CWD decaying at year 0 and carbon in HWPs manufactured before year 0 is excluded.

Benefits of temporary and permanent carbon stock accumulation

When forests sequester CO_2 from the atmosphere, that CO_2 is then stored in biomass and no longer has warming effects on the atmosphere. In a landscape approach, approximately the same amount of biomass is harvested and grown each year. If all harvested biomass was emitted immediately after harvest, the radiative forcing effects from biogenic sources would be approximately 0. However, carbon in harvested-tree root and branch biomass, as well as carbon used in HWPs, may be stored for several years before being emitted back to the atmosphere. This lag in time between sequestration and emission can provide temporary carbon stock accumulation benefits. A portion of the carbon used in HWPs will also be stored permanently in landfills (53). The climate benefit of temporary and permanent carbon stock accumulation, $StockBen_y$, can be quantified by calculating the difference between radiative forcing effects of sequestration and biogenic emissions (equation 11). Biogenic emission sources include CO_2 emissions from forest decay, CO_2 emissions from HWPs, and CH_4 emissions from HWPs.

$$StockBen_y = \sum_s RF_{s,y} * \delta_{s,biogenic} \qquad (11)$$

Results

Overall Carbon Dynamics

Radiative forcing

For all tested forest management regimes, $netRF_{avg}$, which represents the average annual net radiative forcing effect across a time horizon of 100 years for 1000 stands with the same site quality and management, was negative, indicating climate benefits within the time horizon. For all regimes, $netRF_y$, which represents the net radiative forcing effect in year y, had a negative slope (*i.e.*, increasing climate benefits over time) for approximately 10 years, followed by a positive slope (*i.e.*, decreasing climate benefits over time) for the remainder of the time horizon (Figure S2f). For all regimes, CO_2 emissions from HWPs were the largest source of emissions over 100 years, followed by CO_2 emissions from forest decay, fossil fuel emissions from production, and CH_4 emissions from HWPs (Figure S2a-d). Fossil fuel emissions from silvicultural operations and N_2O emissions from fertilizer were very small compared to other emission sources for all regimes.

Carbon stocks

Aboveground carbon stocks were constant for all years in the time horizon within each regime because all carbon is either transferred to another carbon stock pool or emitted to the atmosphere at harvest and is then replaced by approximately the same amount of biomass from that year’s growth on unharvested stands (*e.g.*, Figure S3). CWD and belowground carbon pools took several years to reach a constant state, as decaying biomass accumulated after each harvest until it eventually decayed at around the same rate as its growth. The HWP pool exhibited a similar pattern, in which carbon in shorter-lived products accumulated until eventually it was emitted at around the same rate as new carbon was added to the pool. This trend is evidenced by the slowing rate of growth of the HWP pool overtime. However, the HWP pool continued to grow for the duration of the time horizon because much of the carbon added to landfills and longer-lived products was not emitted, yet carbon continued to be added to these pools.

3.2 Effects of Management

In general, regime characteristics that typically lead to increased productivity (*i.e.*, more biomass grown in less time), such as higher site index, higher density either at planting or throughout (*i.e.*, no thinning), fertilization, and shorter rotations resulted in more sequestration but also more biogenic and non-biogenic emissions. The net climate effects of a regime are represented by the balance between sequestration and emissions, and our results show that the relationship between regime characteristics and net climate effects, estimated by $netRF_{avg}$, are complex (Figure 1).

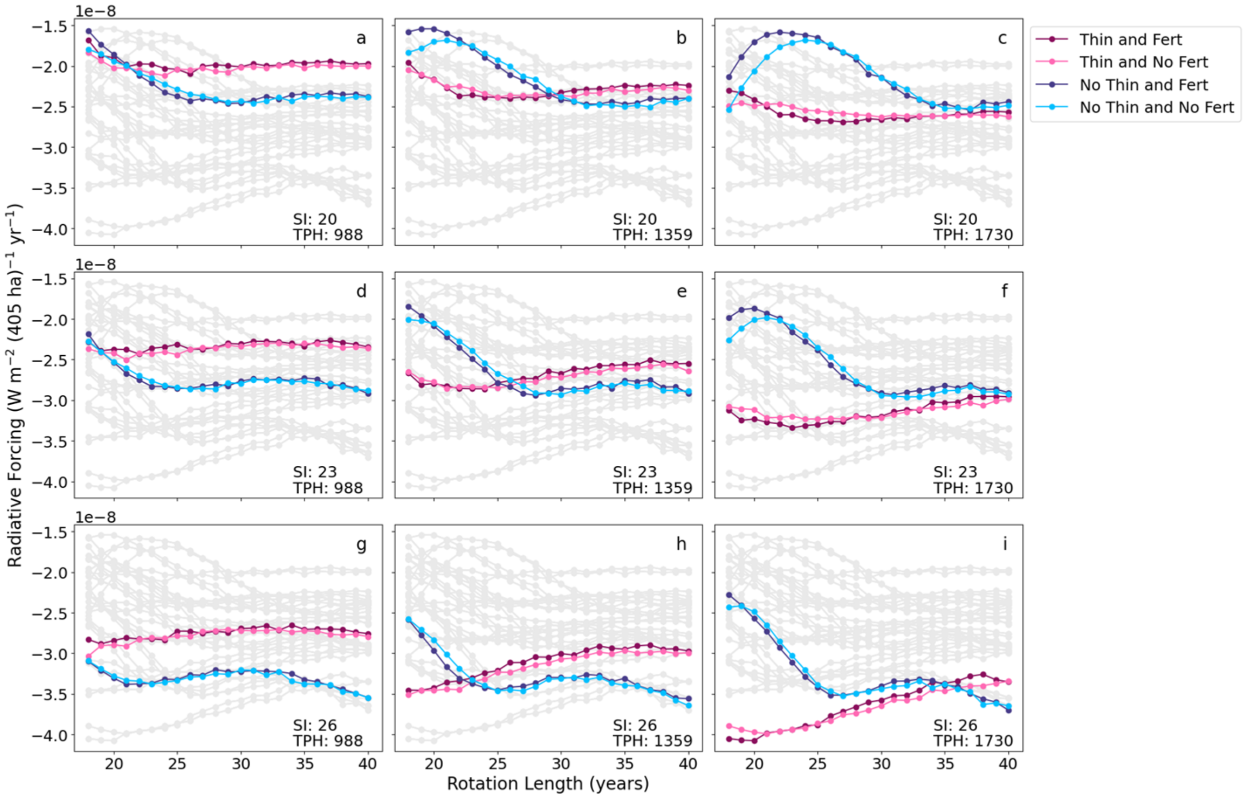

Figure 1. Average annual net radiative forcing (*netRF*$_{avg}$) for forest management scenarios with varying site index and planting density. Forest management scenarios were modeled across a 405-ha landscape of loblolly pine plantations with an approximately uniform age class distribution in the southern U.S. for 100 years. Rotation lengths were repeated across the landscape for all 100 years. Each point represents a single scenario and rotation length combination, and lines connect points for the same scenario. SI = site index is dominant height in m at base age 25; TPH = planting density in trees per hectare; fert = mid-rotation fertilization. More negative values indicate greater climate benefits.

For nearly all regimes, higher site index (as a metric for site productivity) led to more climate benefits (*i.e.*, lower *netRF*$_{avg}$). Planting density had variable effects on *netRF*$_{avg}$, depending on rotation length and thinning scheme). Fertilization had comparatively little net effect. Finally, rotation length had extremely variable effects. For unthinned scenarios, longer rotations generally performed better. For thinned scenarios, shorter rotations performed better or rotation length had little effect. There is considerable variation within these general effects, however, especially for unthinned scenarios. For example, scenarios 21 and 30 (low site quality, high planting density, unthinned, with and without fertilization) show negative climate effects as rotation length is extended from 18 to 22 years, positive climate effects as rotation length is further extended to 37 years, and little effect when rotation length is extended past 37 years (Figure 1c). The extreme variation in the effect of rotation length for unthinned scenarios is likely driven by density-dependent mortality that occurs as stand age increases, allowing remaining trees to reach chip-n-saw and sawtimber size classes, which can produce longer-lived HWPs that require less fossil fuel use for production.

The best-performing regime was scenario 9 (high site quality, high planting density, thinned, with fertilization) on a 20-year rotation. The worst-performing regime was scenario 20 (low site quality, moderate planting density, unthinned, with fertilization) on a 20-year rotation. For low quality sites, management strategies with the most climate benefits include planting moderate to high density stands, thinning, and harvesting after at least 23 years or planting low density stands, not thinning, and harvesting after at least 26 years. For medium quality sites, management strategies with the most climate benefits include planting high density stands, thinning, and harvesting between ages 19 and 30 or planting low density stands, not thinning, and harvesting after at least 25 years. For high quality sites, management strategies with the most climate benefits include planting high density stands, thinning, and harvesting between ages 18 and 25 or planting low-moderate density stands, not thinning, and harvesting after at least 23 years (Table 1). Although the financial feasibility of a silvicultural regime depends on many site-specific factors, some of these management strategies fall within the range of typical commercial practice(54), suggesting that it is possible to manage for both financial and climate goals. Some regimes with high planting density, no thin, and long rotations performed well compared to other management regimes within the same site quality. However, this is not a recommended management strategy because high density, especially in older stands, increases the risk of mortality and weakens forest health(55). Furthermore, if market conditions are such that thinning may be challenging to implement, planting low densities that do not require thinning may help to reduce the risk of density-dependent mortality and the associated negative climate effects, particularly for higher quality sites. The thinning scheme modeled represents only one of many possible schemes, and thinning options such as timing, intensity, method (*e.g.*, row removal), and number of thins likely affect net climate benefits. Finally, the use of mid-rotation fertilization should be tailored to the specific conditions of each site, since a growth response to fertilization greater than the responses modeled in this study will likely outweigh the emissions associated with production and application of fertilizer, increasing climate benefits. Conversely, a lower growth response to fertilization will likely not offset emissions and will therefore decrease climate benefits.

Table 1. Management recommendations for loblolly plantations of three site qualities to achieve the most climate benefits according to the calculated $netRF_{avg}$ for tested regimes

Site quality (SI)	Climate benefits	Planting density (TPH)	Thinning	Fertilization	Harvest age (years)
Low (20)	Optimal	Moderate to high	Thin	Conditional	≥ 23
	Alternative	Low	No thin	Conditional	≥ 26
Medium (23)	Optimal	High	Thin	Conditional	19 - 30
	Alternative	Low	No thin	Conditional	≥ 25
High (26)	Optimal	High	Thin	Conditional	18 - 25
	Alternative	Low to moderate	No thin	Conditional	≥ 23

SI = site index is dominant height in m at base age 25 as a measure of site quality; TPH = trees per hectare; low, moderate, and high planting densities are 988, 1359, and 1730 TPH, respectively; the fertilization recommendation is conditional on the magnitude of individual site responsiveness to fertilization.

Effect of Fossil Fuels

For all regimes, the climate benefits from temporary and permanent carbon stock accumulation, $StockBen_y$, continued to increase for all years within the time horizon. As CWD, roots, and shorter-lived product carbon stocks reached a constant state in which emissions from and additions to these pools were approximately equal, the rate (*i.e.*, slope) at which the benefits of carbon stock accumulation increased was high (*e.g.*, Figure 2). Once this constant state was reached, the rate decreased considerably. Radiative forcing from non-biogenic emissions, on the other hand, continued to increase at a relatively steady rate since there can be no additions to non-biogenic pools to balance out emissions. For some regimes, the benefits of carbon stock accumulation remained larger than the radiative forcing from non-biogenic emissions for the duration of the time horizon. In others, it became smaller in the last few years of the time horizon. Since the slopes of both factors were relatively steady for the last several decades of the time horizon, it is reasonable to conclude that the radiative forcing of non-biogenic emissions would overwhelm the benefits of carbon stock accumulation for all regimes within a few decades if the study time horizon were extended.

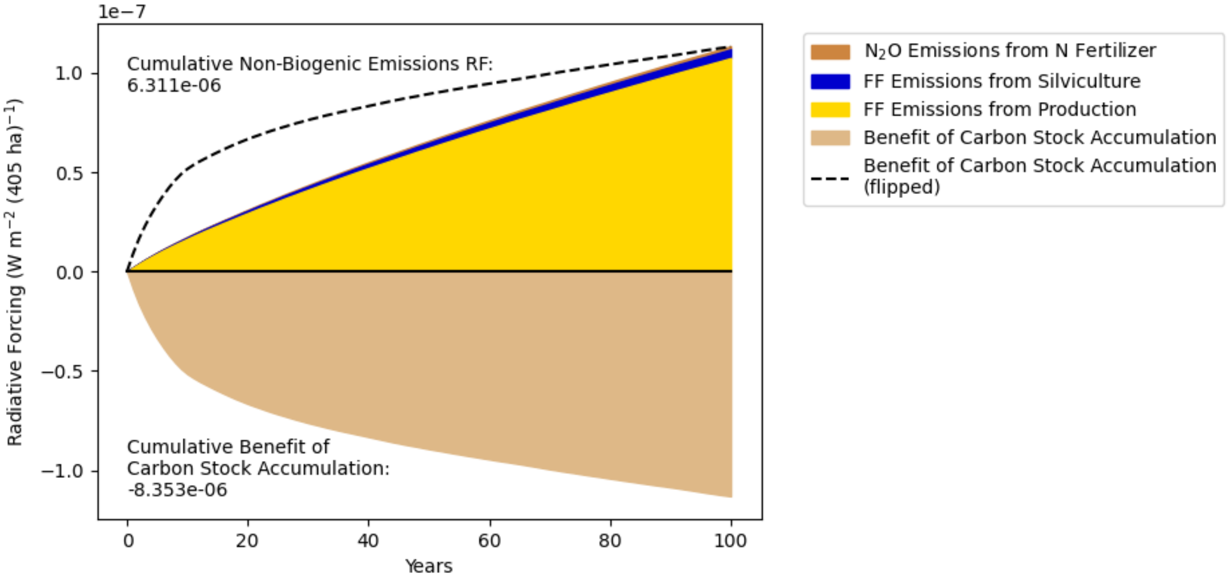

Figure 2. Radiative forcing from non-biogenic sources ($RF_{s,y}$) and climate benefit of carbon stock accumulation ($StockBen_y$) across a 405-ha landscape of loblolly pine plantations in the southern U.S. for forest management scenario 1 with rotation length of 25 years. The landscape has an approximately uniform age class distribution, such that approximately the same amount of biomass is grown and harvested in any given year. Scenario 1 represents a landscape with a site index of 20 m, planted with 988 trees per hectare, thinned at age 15 to 16 m^2 ha^{-1} of basal area, and fertilized at age 16 with 224 kg ha^{-1} of nitrogen and 28 kg ha^{-1} of phosphorus. N = nitrogen; FF = fossil fuel. N_2O emissions from N fertilizer refer to the N_2O emissions that result from the denitrification of nitrogen fertilizer applied at mid-rotation; FF emissions from silviculture refer to upstream emissions from the production of seedlings, herbicide, and fertilizer, as well as emissions from bedding, application of herbicide and fertilizer, and harvesting; FF emissions from production refer to the CO_2 emissions from fossil fuel use for the transportation of timber from the harvest site to the mill and production of HWPs at the mill; benefit of carbon stock accumulation refers to the difference between the radiative forcing of forest sequestration and all biogenic emissions, in the year in which each occurs; the black dotted line represents the positive

values of the benefit of carbon stock accumulation, such that comparison with radiative forcing from non-biogenic sources is convenient. Positive values indicate warming effects, and negative values indicate cooling effects.

Effect of the Metric of Interest

When the metric used to measure climate benefits is average carbon stock (C_{avg}), scenarios with characteristics that increase productivity, including higher site index, higher density both at planting and throughout (*i.e.*, no thinning), and fertilization, consistently performed better than corresponding scenarios with less productive characteristics. This trend is similar to the effects of management on the radiative forcing from sequestration (*i.e.*, excluding emissions). Unlike the effect of rotation length on sequestration, however, regimes with longer rotations outperformed corresponding regimes with shorter rotations for all regimes when C_{avg} was the metric used for comparison (Figure 3).

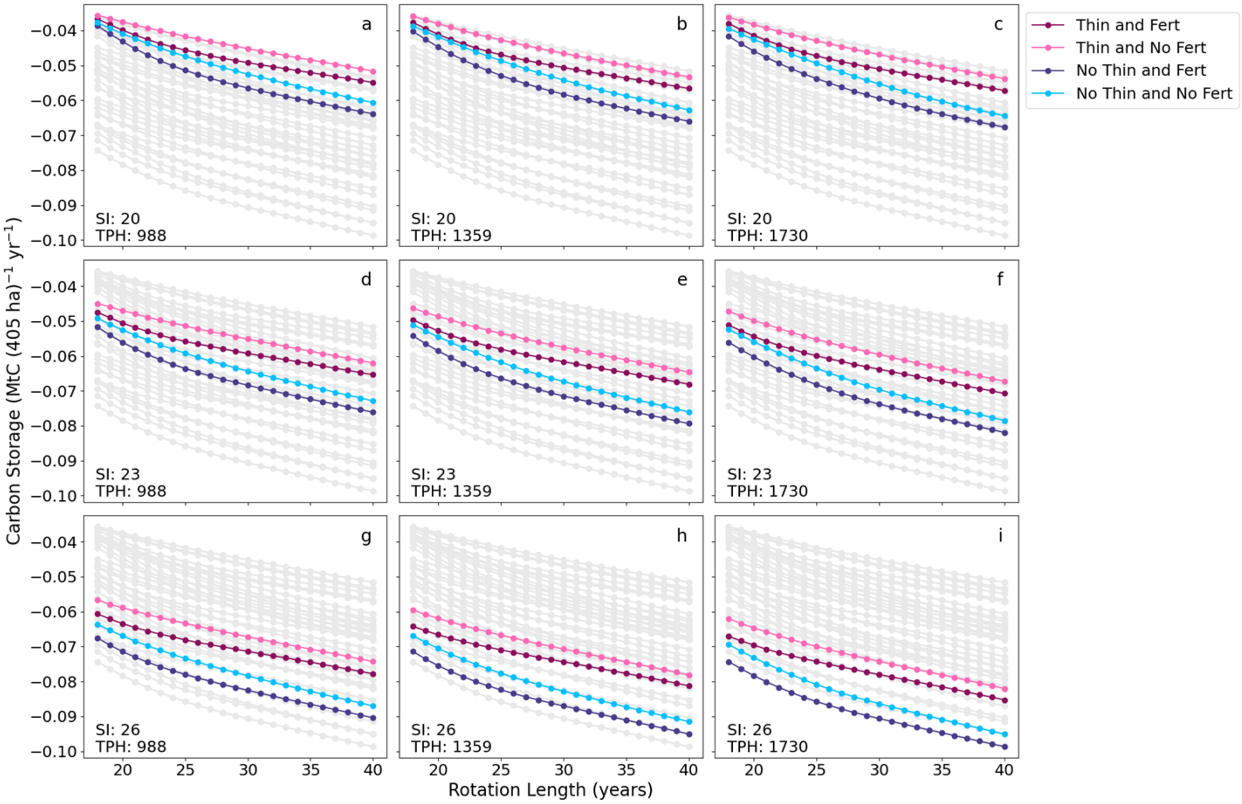

Figure 3. Average annual carbon stock over 100 years in *in situ* and *ex situ* pools (C_{avg}) for forest management scenarios with varying site index and planting density. Forest management scenarios were modeled across a 405-ha landscape of loblolly pine plantations with an approximately uniform age class distribution in the southern U.S. for 100 years. Rotation lengths were repeated across the landscape for all 100 years. Each point represents a single scenario and rotation length combination, and lines connect points for the same scenario. SI = site index is dominant height in m for base age 25; TPH = planting density in trees per hectare; fert = mid-rotation fertilization. More negative values indicate greater climate benefits.

Discussion

We found that the dynamic LCA approach using net radiative forcing (*i.e.*, $netRF_{avg}$) allowed for a more nuanced understanding of the climate effects of forest management and site quality than carbon stock estimates (*i.e.*, C_{avg}) for loblolly pine in the southern U.S. When net radiative forcing is used for comparison, our results show that management decisions such as thinning and rotation length should be adjusted based on stand-specific conditions, and that overgeneralized strategies, such as extending rotation lengths, lowered or had little effect on climate benefits for many scenarios.

When $netRF_{avg}$ was used to indicate climate effect, the results showed that increasing site quality substantially increased climate benefits for all scenarios. Similar findings have been reported in the literature for loblolly pine (9,12). However, the effects of planting density, thinning, and rotation length on $netRF_{avg}$ varied greatly depending on the other characteristics of the regime. In many cases, characteristics that promote high diameters at earlier ages with moderate stocking levels (*e.g.*, high site quality or thinning when density is high) resulted in greater benefits when shorter rotations were employed. Characteristics that yield higher diameter growth only later in the rotation (*e.g.*, low site quality or not thinning when density is high) resulted in greater benefits when longer rotations were employed. This trend is supported by Zhao et al. (56,57), who found that more intensive management and higher site quality generally led to higher sequestration rates in young loblolly pine stands, followed by lower sequestration rates in older stands.

Our results further showed that mid-rotation fertilization had little net climate effect, which is somewhat contradictory to other studies showing fertilization to increase carbon sequestration (8,58). This discrepancy may be due in part to an underestimated growth response to fertilization in the FASTLOB growth and yield model we used, compared to recent estimates of growth response by Albaugh et al. (59) However, the primary factor contributing to this discrepancy is likely our use of a climate-focused metric that includes temporal effects of emissions from fertilizer production and application, as well as changes in sequestration. Variations in sequestration or emissions, due to site-specific growth response or improved fertilizer production or application efficiency, may lead to heightened or diminished climate benefits.

Several of the management recommendations for climate benefits involved planting high densities and thinning. However, a variety of uncertainties surrounding this approach suggests it may not always be the most effective option. Stands with higher densities are at greater risk for forest health issues, such as pest outbreaks, as well as for density-dependent mortality. Higher mortality results in higher emissions from forest decay, which likely occur sooner than if the wood had been harvested and made into products. Furthermore, our results may underestimate emissions from tree mortality, since we do not account for emissions of decaying CWD prior to harvest. Specific thinning schemes vary in timing, intensity, method (*e.g.*, row removal), and number of thins, and different thinning schemes may have different climate effects depending on site-specific conditions. Finally, some landowners may face challenges in securing loggers who are willing to conduct thinnings. Planting low-density stands can eliminate the risk of having overstocked stands if thinning becomes infeasible (60).

Carbon stocks failed to identify management strategies with the most climate benefits in many cases, since many regimes that produced comparatively high carbon stocks also produced comparatively low climate benefits, and vice versa. Higher carbon stocks primarily indicate higher sequestration and stock accumulation but omit important emissions components, leading to incorrect conclusions. For example, carbon stock estimates were consistently higher with longer rotations. Longer rotations are often used as a forest management strategy to increase forest carbon stocks (61). This strategy is potentially problematic for two reasons. First, although we found that for individual scenarios, longer rotations increased carbon stocks, many regimes with short rotations had higher carbon stocks than other regimes with longer rotations and different management. For example, on high-quality sites with moderate planting density, the unthinned fertilized scenario (S26) with a 20-year rotation had higher carbon stocks than the thinned fertilized scenario (S8) with a 30-year rotation. Puls et al. (12) similarly found that a 20-year rotation may lead to higher carbon stocks than a 30-year rotation for certain management and site quality combinations. Second, the fundamental goal of most climate change mitigation efforts is to reduce atmospheric warming. Therefore, metrics that directly represent the effect of a forest system on atmospheric warming, such as net radiative forcing, should be used to determine effective management strategies for forest-sector mitigation efforts.

The results were also somewhat sensitive to the chosen temporal boundary, despite substantial efforts in the methodology designed to avoid such effects. For all regimes, the annual net radiative forcing, $netRF_y$, increased over time in the last several decades of the study. A longer time horizon would therefore indicate fewer net climate benefits for all regimes, assuming this trend is maintained past 100 years. The temporal boundary also included only GHG fluxes from stands harvested in or after year 0. When compared to real-world GHG fluxes from the forest sector for any year, all sequestration is included but emissions from biomass and HWPs produced in previous rotations are not included. Thus, estimates of $netRF_y$ appear lower (*i.e.*, more climate benefits) than if all emissions from a given year were included. This discrepancy is especially true for earlier years when inputs to decaying root, CWD, and shorter-lived HWP pools are still greater than outputs from those pools.

Aside from the temporal effects of decaying biomass and shorter-lived HWP emissions, two main factors drove $netRF_y$: (1) the amount of carbon accumulated in long-term and permanent stocks in longer-lived products and landfills and (2) the extent of fossil fuel use. These factors essentially removed (stock accumulation) and introduced (fossil fuel use) carbon from and to the fast carbon cycle within the timescale of the study. Puls et al. (12) similarly found factors related to landfill carbon stocks, such as the portion of HWPs that is permanently stored in landfills, to have high influence on emissions from southern pine HWPs. For all regimes, the annual radiative forcing benefit from carbon stock accumulation, $StockBen_y$, increased over time at a slower rate than the radiative forcing effect from fossil fuel emissions. This trend indicates that climate benefits from forest systems are decreasing over time due to greater warming effects from fossil fuel emissions than cooling effects from long-term and permanent carbon stock accumulation. Schulte et al. (62) similarly found that the radiative forcing from value chain fossil fuel emissions significantly outweighed the radiative forcing from biogenic carbon for a pulp-based beverage carton product when substitution effects were not considered. Our finding highlights the need to reduce fossil fuel use within the forestry sector through the increased use of renewable energy sources or increased energy efficiency. In addition to reducing fossil fuel emissions, increasing carbon stock accumulation through longer product lifespans, more efficient landfill storage, or carbon capture systems (*e.g.*, bioenergy with carbon capture and storage (BECCS)) would also help offset the effects of fossil fuel use.

Advances in forest management methods and genetics have significantly improved loblolly plantation productivity over the past few decades (11,63,64), and these gains will likely continue in the future. Changing climatic factors such as CO_2 concentrations and precipitation will likely also affect future productivity, potentially in climate beneficial ways (65). We provide an exploratory sensitivity assessment on the effect of rising productivity over time on net radiative forcing in the Supplementary Information, but further analysis is needed to incorporate empirical data and discern the specific effects of each productivity driver. Finally, the management recommendations presented in this study are based solely on the net radiative forcing calculated for each regime and are not necessarily financially viable for the landowner; nor do they consider the societal benefit of producing low-emission materials for energy, construction, and other uses (*i.e.*, substitution). Further research is needed to identify the most climate-beneficial management strategies that are financially feasible for landowners, with and without payments for climate benefits, and to analyze the economic and land-use ramifications of management changes.

By modeling radiative forcing of forest management regimes applied to a 405-ha landscape of loblolly pine plantations in the southern U.S., we show that regime characteristics associated with high productivity, such as high site quality and high stand density, result in greater atmospheric cooling effects from sequestration but also greater warming effects from emissions. The effects of management on the net radiative forcing balance of regimes are complex, and detailed accounting methods that capture these complexities should be used in future research and policy design. Generalized strategies for achieving maximum climate benefits include adjusting thinning and fertilization to stand-specific conditions. Optimal rotation lengths vary based on site quality and management, and in many cases, extended rotations resulted in similar or even less climate benefits than shorter rotations. Two metrics for climate effect were calculated: net radiative forcing and total carbon stocks. Net radiative forcing, calculated according to dynamic LCA methodology, accounts for all GHG flows in the year they occur and their subsequent warming or cooling effect on the atmosphere. Carbon stocks account only for sequestration and continued storage in biomass and wood products but ignore the effects of non-biogenic and non-CO_2 emissions. Net radiative forcing is a more appropriate metric to assess climate effects, and our results show that carbon stocks do not accurately represent the climate effects of forest management strategies. Our findings highlight the need for accounting methods in forest carbon research, policy, and offset protocols that more accurately reflect atmospheric warming effects of forest mitigation strategies.

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Author contributions

Sarah J. Puls – methodology; software; formal analysis; visualization; writing – original draft. Rachel L. Cook – conceptualization; writing – review and editing; supervision; funding acquisition. Justin S. Baker – validation; writing – review and editing; supervision. James L. Rakestraw – supervision; project administration; funding acquisition.

Competing interests

This paper was part of a special project funded by International Paper, through the Forest Productivity Cooperative. The authors have no competing financial or non-financial interests to declare related to this research.

Data Availability

Growth and yield model(28,29) outputs for all tested regimes are provided in the Supplemental Information. Data for carbon stocks and emissions from harvested wood products were generated using the LobWISE 1.1 model(12), which is available for researchers upon request. All subsequent calculations were performed in the programming software, Python 3.11.1. The annual averages for all tested regimes and all metrics generated from these calculations are provided in the Supplemental Information.

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