

ABSTRACT

PULS, SARAH J. Modeling Carbon and Climate Impacts from Harvested Wood Products in Loblolly Plantations in the Southern US. (Under the direction of Drs. Justin Baker and Rachel Cook).

Forests are a crucial component of climate change mitigation, and determining the most effective implementation of mitigation strategies requires accounting methods and tools that can accurately model greenhouse gas (GHG) fluxes associated with forests. Two primary categories of GHG fluxes from the forest sector are *in situ* and *ex situ* fluxes. *In situ* fluxes refer to emissions and removals of GHGs that occur within the forest ecosystem, and *ex situ* fluxes refer to emissions of GHGs that occur outside the forest ecosystem, such as emissions from burned or decaying harvested wood products (HWPs). In this project, we design and parameterize a model that projects *ex situ* carbon flows for harvested wood products manufactured from southern pine, including biogenic and fossil fuel emissions, for 120 years after harvest. We then use this model to assess carbon storage and emission trends for southern pine harvested wood products and to identify forest management strategies for loblolly pine plantations in the southern US that have the highest climate change mitigation potential.

We estimate that wood products from annual loblolly and shortleaf pine timber harvests across the southern US store 29.7 MtC in the year they enter the market, and 11.4 MtC remain stored after 120 years. We estimate fossil fuel emissions from the procurement, transportation, and manufacturing of these wood products to be 43.3 MtCO_{2e} year⁻¹. We found that composite logs, used to manufacture oriented strand board (OSB), were the most efficient log type for storing carbon, storing around 1.8 times as much carbon as saw logs per tonne of log over 120 years. Possible areas for reduction of *ex situ* emissions include reducing decay of wood products in landfills, increasing methane capture from landfill decay, reducing fossil fuel emission rates from pulp and paper production, expanding storage in key products, such as corrugated boxes, by extending product lifespans and recycling, improving sawmill efficiency, and reducing waste from construction.

Optimal forest management strategies for climate benefits varied considerably depending on individual stand conditions, such as site quality and planting density. Generally, thinning is recommended when density is high and not recommended when density is low. Higher site quality led to more climate benefits. Fertilization had comparatively little net effect. Optimal rotation lengths varied depending on stand conditions, and in many cases, extended rotations resulted in similar or even less climate benefits than shorter rotations. These results highlight the need to manage forests for climate on a stand-specific basis, rather than applying generalized management strategies, such as extended rotations, to all stands. Using carbon storage as the metric of interest, we failed to identify management strategies with the most climate benefits in many cases, since many regimes that produced comparatively high carbon storage also produced comparatively low cooling effects, and vice versa. This result emphasizes that GHG accounting methodologies 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. Finally, although we show that loblolly pine plantations are net GHG sinks on average over the study time horizon, climate effects of fossil fuel use accumulate faster over time than effects of storage in forests and wood products, emphasizing the need to reduce forest-sector fossil fuel emissions and improve storage in products, landfills, and carbon capture technologies.

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Modeling Carbon and Climate Impacts from Harvested Wood Products in Loblolly Plantations in
the Southern US

by
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BIOGRAPHY

Sarah Jane Puls was born in Oklahoma City, Oklahoma. Growing up, her passion for nature was ignited through hiking trips to Yellowstone and Rocky Mountain National Parks. Her journey led her to Guiyang, China, where she studied Mandarin Chinese while teaching English to children. Witnessing the escalating global climate change crisis fueled her determination to effect tangible change. She decided to pursue an education in natural resources, aiming to contribute to international efforts leveraging natural climate solutions. She received a B.S. in Natural Resources from NC State University, with minors in forestry and Chinese language. Driven by a desire to add meaningful contributions to climate change mitigation research, she pursued graduate studies analyzing how to best manage forests for the most climate benefits. Her research focuses on carbon storage and emissions from wood products and forest management strategies for climate change mitigation in forest plantations. Her work centers on loblolly pine plantations in the southern US, but she is excited about the application of her research to other forest types and regions worldwide.

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CHAPTER

----- 1 -----

INTRODUCTION

Forests are a crucial component of climate change mitigation, and many strategies have been proposed to maximize their mitigation potential. These strategies include expanding forest land use (*e.g.*, afforestation, reforestation, urban reforestation), avoiding emissions from forest conversion to other land uses, risk reduction treatments (*e.g.*, fuel reduction treatments for wildfire prone forests), substitution of wood products for products with higher associated emissions (*e.g.*, wood pellets, mass timber), and improved forest management (*e.g.*, extended rotations or improving forest productivity). Determining the most effective implementation of these mitigation strategies requires accounting methods and tools that can accurately model greenhouse gas (GHG) fluxes associated with forest management. Such tools can help to assess the climate effects of management and policy decisions and choose pathways with the highest mitigation potential.

Two primary categories of GHG fluxes from the forest sector are *in situ* and *ex situ* fluxes. *In situ* fluxes refer to emissions and removals of GHGs that occur within the forest ecosystem, such as sequestration through photosynthesis and emissions from decaying vegetation. These fluxes are relatively well-studied, and many modeling tools exist that estimate these fluxes for various forest types and management conditions. *Ex situ* fluxes refer to emissions of GHGs that occur outside the forest ecosystem, such as emissions from burned or decaying harvested wood products (HWPs). These fluxes are less well-studied, and more detailed models capturing HWP carbon flows and emissions for specific geographic regions and forest types are needed. In this project,

we focus on wood products manufactured from southern pine grown in the southern US and develop modeling frameworks that link *in situ* and *ex situ* sequestration and emissions fluxes and associated climate impact metrics. This study advances the scientific literature on the role of managed forest plantations in contributing to broader climate mitigation strategies.

1.1 Southern Pine Forests in the Southern US

The southern US is known as the nation's "wood basket" and is by far the most productive region of the country for timber production. The region is defined as including Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia (1). Four species of pine, commonly referred to as southern pine, make up around 21% of southern forestland area (2). They include loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata* Mill.), and slash pine (*Pinus elliottii* Engelm.) (3). Of these species, loblolly pine is the most productive and makes up around 83% of planted southern pine timberland (2). Loblolly pine plantations are typically planted with genetically improved seedlings and are often intensively managed, using management tools such as chemical site preparation, mechanical site preparation and bedding, fertilization at establishment, early herbaceous weed control, thinning, mid-rotation fertilization, and mid-rotation woody release (4,5). The most common wood products made from loblolly pine timber are pulp and dimensional lumber (1). Other common products include plywood, composite and engineered products, poles and pilings, and biofuel (1,3,4).

Pine plantation management can significantly impact the product mix made from harvested pine timber. For example, planting fewer trees per acre, reducing competition from non-crop tree vegetation, planting improved genetics, thinning, applying fertilizer, and extending rotations can increase the portion of harvested logs with a high diameter, such as sawtimber, veneer, and pole logs (4,6–8). Management can also impact carbon storage. For example, large logs store more carbon than smaller logs, and are typically used, in part, to make longer-lived wood products, such as housing, buildings, and utility poles, thereby storing carbon for many years after harvest. However, loblolly pine plantations are typically more productive in early years (9), and taking advantage of high sequestration rates in young stands by maintaining shorter rotations could

potentially lead to higher net land carbon fluxes over time, which could support efforts to maintain or increase annual carbon sinks in the US. Using a relatively simple model for carbon storage duration in HWPs, Gonzalez-Benecke et al. (10) found that longer rotations stored more carbon in loblolly plantations over 200 years than shorter ones. However, more research is needed to document the flow of carbon in HWPs and analyze the effect of forest management on these flows.

1.2 Life Cycle of Carbon in Harvested Wood Products

As forests grow, CO₂ is sequestered from the atmosphere through photosynthesis and stored in tree stems, branches, foliage, and roots. When forests are harvested, carbon stored in tree roots, branches, and foliage is typically left on site and decays back to the atmosphere over some period of time. Most of the stem carbon is removed from the harvest site as logs and transported to a mill to be made into wood products. At the mill, a portion of the log carbon is removed as mill residue (e.g., sawdust, bark, wood chips). The remaining carbon is processed into a primary product, such as lumber or pulp. Carbon in mill residues are typically repurposed for energy, such as sawdust burned in sawmill kilns (11), or other wood products, such as wood chips used for pulp production (12). Carbon in primary products is then manufactured or constructed into a secondary product, such as corrugated boxes or housing. At the end of the product's lifetime, the carbon may then be recycled or downcycled into another secondary product, incinerated, or landfilled (13). Carbon that is landfilled may be emitted back to the atmosphere as CH₄ or CO₂ as the products decay, though a significant portion remains stored in the landfill and does not decompose (14,15). Soon after harvest, forest stands are replanted and the cycle repeats. As both vegetation and HWPs decay or are combusted over time, the carbon that was sequestered by the forest is released back to the atmosphere. Any carbon that is sequestered but not released, such as carbon permanently stored in landfills, is considered a permanent sink (15). Fossil fuels are also combusted in this process, such as by harvest equipment, trucks transporting logs to mills, and mill processes. To analyze the net effect of all GHG fluxes from loblolly pine plantations and HWPs, as well as the relationship between this effect and forest management practices, requires detailed estimates of carbon flows in *in situ* and *ex situ* pools as well as flexible metrics to capture climate effects of these flows.

1.3 Carbon Accounting Metrics

Three key metrics are often employed in carbon or GHG accounting: sequestration, emission, and storage. Each term has a distinct definition, and precise application of these terms, both in language and in methodology design, is crucial to ensure that proposed climate actions yield genuine and intended climate effects. Sequestration refers to the active process of removing GHGs from the atmosphere, such as through photosynthesis. Emission refers to the active release of GHGs into the atmosphere, such as through decay or combustion of organic material or fossil fuels. Both sequestration and emission indicate changes in the atmospheric concentration of GHGs. These changes have effects on atmospheric warming not only for the year in which the change occurred, but for the lifetime of the GHG in the atmosphere. Storage refers to a material, such as tree biomass or wood, that retains carbon within itself. Unlike sequestration and emission, it does not refer to changes in atmospheric GHG concentrations; rather, it is an instantaneous account of the amount of carbon held in a given pool at a specific point in time. Storage at two different points in time can thus be used to calculate sequestration (*i.e.*, positive change) or emissions (*i.e.*, negative change) over that time period. Because storage does not represent a change in atmospheric GHG levels, it should not be directly compared with emissions. In other words, 1 tCO₂ emitted does not have the same climate effect as 1 tCO₂ held in storage. Furthermore, GHGs that are sequestered are often released back to the atmosphere after some period of time, such as sequestered forest carbon that is released by vegetation decay after harvest. The climate effect of temporarily storing carbon in forests or HWPs is highly debated (16–24), and numerous methodologies have been proposed to account for these effects (*e.g.*, 25–28). Studies examining forest carbon should apply appropriate metrics and ensure transparency in interpreting results to accurately convey the implications and limitations of the findings (20).

1.4 Project Goals

The purpose of this project is to identify forest management and product allocation strategies for loblolly pine plantations in the southern US that have the highest climate change mitigation potential. We design and parameterize a model that projects *ex situ* carbon flows for harvested

wood products manufactured from southern pine, including biogenic and fossil fuel emissions, for 120 years after harvest. We use this model to analyze various aspects of carbon flows from loblolly pine plantations, such as the sensitivity of GHG fluxes to key model parameters and the effect of simplified forest management scenarios on carbon storage. We then develop and employ a comprehensive methodology to compare the effects of an extensive set of management scenarios on atmospheric warming, accounting for the timing of sequestration and emissions from *in situ* and *ex situ* pools. Throughout this project, considerable effort was directed towards maintaining transparency surrounding the metrics used to quantify mitigation potential and the implications of those metrics for real climate effects.

CHAPTER

----- 2 -----

MODELING WOOD PRODUCT CARBON FLOWS IN SOUTHERN US PINE PLANTATIONS

2.1 Introduction

According to the 2022 IPCC Climate Change Mitigation Report, net CO₂ emissions from 2010 to 2019 were around 33% of our remaining carbon budget from 2020 onwards for a 67% probability of limiting global warming to the 2°C limit (29). Effective climate change mitigation requires efforts across many sectors to both reduce emissions of greenhouse gases (GHG) and to actively remove them from the atmosphere (29). The global forest sector is in a unique position to contribute to these mitigation goals. Harris et al. (30) estimate that, globally, forests sequester around 7.6 GtCO₂e year⁻¹, and recent estimates (31) indicate that the global forest sector could support an additional 1.2-5.8 GtCO₂e year⁻¹ in carbon sequestration under climate policy incentives. Studies have highlighted the potential role of wood-based bioenergy (32,33) and wood product substitution for more energy-intensive materials (34) as important mitigation strategies. Other studies point to forest carbon gains from deferred harvests, reforestation, or risk mitigation efforts (10,35,36). Forests also provide wood products, which continue to store an estimated 335 MtCO₂e year⁻¹ globally after harvest (37), impacting the total carbon storage capacity of forest stands over time. However, despite the significant impact of wood product carbon storage on total forest carbon, wood products are often excluded from modeling efforts to evaluate possible forest sector mitigation strategies.

Studies that do include wood product carbon vary considerably in their findings. One recent study suggests that harvested wood products (HWPs) could generate a substantial source of emissions globally over the next decade using a simulation approach that ignores systematic changes in forest productivity and management responses to growing wood demand (38). Other recent studies using economic models that capture interactions between forest product markets and management interventions suggest that wood product and terrestrial forest carbon pools can grow jointly at global and regional scales under certain market and policy conditions (31,39,40). Integrated assessment and forest sector models that more adequately capture the complexities of carbon flows in processing and final wood product streams are required to inform management and policy changes and optimize wood product and forest carbon storage for climate mitigation.

Further, while there is a large and growing literature that has applied attributional life cycle analysis techniques to simulate wood product carbon flows, these analyses often do not capture interactions between HWP carbon flows and forest management regimes, which can affect both carbon sequestration and wood product disposition. More detailed accounting of wood product carbon flows is particularly important for high productivity commercial species where adjustments to silvicultural management regimes (*e.g.*, rotation length) across many stands could have significant effects on forest sector carbon storage.

Southern pine plantations offer a unique opportunity to analyze HWP carbon through this approach in a way that contributes significantly to climate change mitigation strategy for the US. Composed primarily of loblolly pine (*Pinus taeda* L.), southern pine plantations account for 22% of forest area, 71% of all planted timberland, and 51% of forest growth in the southern US (4). Collectively, the southern US produces around 60% of US timber products and more timber than any individual country in the world (41).

The goal of this study is to provide a current comprehensive analysis of the wood product carbon flow associated with southern pine grown in the southern US and identify several potential areas of improvement for climate benefits. Our objectives are to 1) create a novel modeling framework that can project *ex situ* carbon flows across different wood product pools and over time and is adaptable to different species and regions, 2) develop parameters to adapt this framework to

southern pine grown in the southern US, 3) evaluate the sensitivity of loblolly and shortleaf pine *ex situ* carbon flows to key model parameters (*e.g.*, lifespan, milling efficiency, and recycling rates), 4) link the developed framework with a growth and yield model to assess total (*i.e.*, *in situ* and *ex situ*) carbon storage from two common silvicultural management regimes for loblolly pine plantations (20-year pulpwood regime, and 30-year sawtimber regime), and 5) compare the estimated business as usual carbon flows from loblolly and shortleaf pine wood products to hypothetical wood usage scenarios involving changes in wood consumption and technology parameters.

2.1.1 Wood Product Carbon Modeling Background

Wood product carbon models are used to estimate and project stored carbon over time for various purposes. HWP carbon was accepted as part of a country's GHG reduction contributions at the 17th Conference of the Parties (COP17) and must be reported by all Annex I Parties. The US Environmental Protection Agency (EPA) adopted the methodology developed by Skog (42) for harvested wood product stock estimates in national greenhouse gas inventories (43). HWP carbon is sometimes included in carbon offset projects as an additional benefit from changes in forest management associated with the project (44,45). HWP carbon may also be used in decision making for sustainable forest management, studies analyzing the effectiveness of climate change mitigation strategies, carbon inset accounting (*i.e.*, reducing GHG emissions or increasing removals within an actor's own supply chain, such that the actor's net emissions are reduced), and the design and evaluation of climate smart commodities programs (46–52).

Typical wood product carbon models use some input of harvested timber, whether from a growth and yield model or actual harvest data, and sort the timber by product class (13,53–56) and either species type (*i.e.*, softwoods or hardwoods) (53,55,56) or forest type (57,58). These models typically simulate a milling process through mill efficiency factors that may be specific to product class, species type, and/or region. Mill residues, such as wood chips and bark, are often considered to be immediately emitted (53,56,59), though some models attempt to capture a simplified version of residue carbon flow (60). Fossil fuels burned in the procurement, transportation, or milling process are sometimes accounted for in these models (59,60). A portion of stored carbon is sometimes deducted between the milling process and the products' useful life to account for

construction or manufacturing waste (56). After the simulated milling process, products enter use and are typically transitioned out of use according to a first-order decay formula with half-lives for each category of primary products (lumber, plywood, paper, etc.) (57,61). If the recycling of products such as paper is included, it is typically built into the half-life parameters (57). After their useful life, products are discarded into landfills or burned. Models often categorize carbon at reported years as being either still in use, emitted with energy capture, emitted without energy capture, or in a landfill (53,55–57,59,62). After being landfilled, some portion of product carbon typically continues to decay according to solid wood-specific and paper-specific half-lives (56,59,63,64).

Though these models vary in complexity and use a wide range of parameters, their boundaries are similar, beginning with some regional or national timber input and reporting carbon stock estimates derived from that timber. While this approach is sufficient for stock estimates, when analyzing the carbon potential of alternative mitigation strategies, this approach considers only one component of a larger system (65). A wood product carbon model parameterized for a specific species and region that can be linked with a forest carbon model for the same species and region has the potential to analyze trade-offs between carbon sequestration/storage in wood product pools and forest systems. For example, there are trade-offs involved in the timeline of both the forest systems that grow the wood and the use and disposal of the wood products. Many products that remain in use for a shorter period of time are grown in forest systems with shorter rotations, and vice versa. Therefore, though the longer-lived products will store more carbon in the HWP pool over time, the shorter-lived products are concurrent with younger forest systems that sequester carbon at a faster rate. Rotation lengths also vary greatly among species and forest ownership types, suggesting that the most effective mitigation strategy within the context of one species or ownership type may not be the most effective in another.

Significant losses also occur when carbon is transferred from *in situ* carbon, or carbon in the forest, to *ex situ* carbon, or carbon in wood products. The US Forest Service estimated harvest residue (*i.e.*, growing and non-growing stock) from softwood removals in the southern US to be around 16% of the aboveground tree carbon (66). Estimates for belowground tree carbon are rarely included post-harvest though significant amounts can remain for decades (67). More carbon is

emitted during the milling process, as mill residue is used to fuel production (68). Additionally, forest managers, especially in the context of plantations, have considerable control over both the carbon sequestration rates of a forest stand and the types of wood products that will be produced when the stand is harvested. Silvicultural management tools such as rotation length, planting density, fertilization, herbicide application, genetic material, and thinning are all used to manipulate forest sequestration rates (*i.e.*, growth rates) and timber product classes at harvest. Therefore, in order for forest sector carbon modeling to be meaningful, it must link wood product carbon with the specific forest system (*e.g.*, species, region, management, etc.) from which the products originate and have the ability to incorporate *in situ* and *ex situ* carbon synchronously over time.

2.2 Model Documentation and Methods

2.2.1 LobWISE Model Description

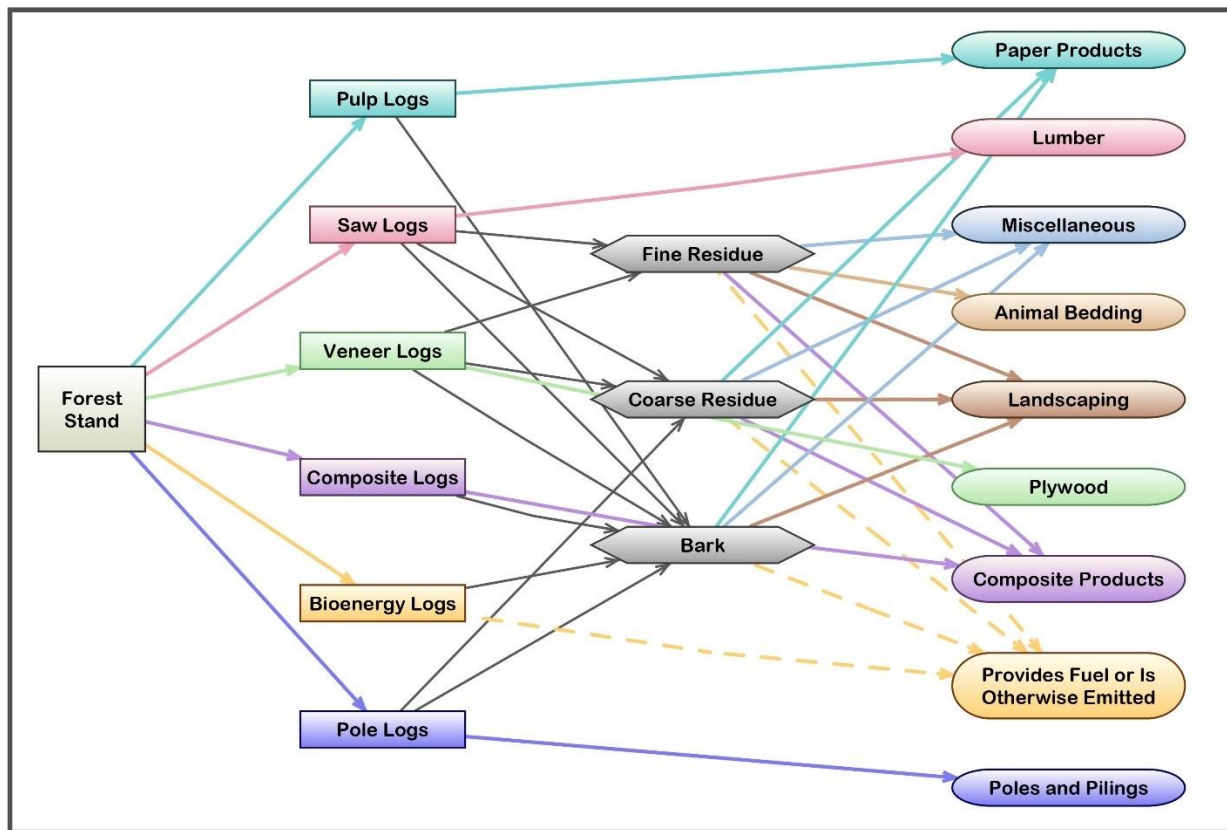


Figure 2.1. Flow of carbon from harvest, through the milling process, and into primary products.

This study uses elements of a life cycle assessment (LCA) approach to create a framework, based in Microsoft Excel, that traces wood product carbon through five processes: (1) harvest, (2) milling (Figure 2.1), (3) post-mill manufacturing, construction, and use, (4) recycling, downcycling, and landfilling, and (5) emission (Figure S1). The framework takes inputs of four different log size classes or eight different log types, in either green weight or volume, and returns a number of outputs, including carbon remaining stored in various uses and in landfills at any given point in time, biogenic CO₂ and methane emissions, and fossil fuel emissions associated with the production of the HWPs. The parameters for the framework can be developed for any species or region if data are available and updated as consumption patterns and technology change and new studies shed light on uncertainties.

System Boundaries

For this study, we construct a model, LobWISE (Loblolly Wood Inventory, Storage, and Emissions), by developing parameter values (Tables A1-25) for the proposed framework that are specific, where data exist, to loblolly pine grown in the southern US. The following model description is specific to LobWISE, which was used to conduct the analyses in this study, but the concepts and formulas described are those used in the adaptable framework as well.

Where data exist, LobWISE is specific to carbon that originated from loblolly pine grown in southern US forests, regardless of where the products are consumed. The southern US is defined as including Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. It assumes that exported products are consumed similarly to domestic products and that there is a national market for wood products. Since most wood product data only distinguish between softwoods and hardwoods, rather than between species, softwood was frequently used to represent loblolly wood. Four species of pine in the southern US are typically referred to as southern pine: loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata* Mill.), and slash pine (*Pinus elliottii* Engelm.). The wood from these four species is similar and is used for the same products (3). Therefore, though this study focuses on loblolly pine because of its prevalence in southern pine plantations, it is appropriate to derive wood product carbon outputs from LobWISE for any of the southern pine species. The framework produces 120 years of outputs after the initial harvest

to be consistent with the common 100-year definition of permanence in carbon offset accounting and national stock estimations and to allow for the comparison of 20- vs. 30-year loblolly pine rotations that was conducted in this study. Year 0 is considered to be the time at which the wood products enter the market, thus we do not account for cumulative storage or emissions from an existing wood product stock.

Harvest

Inputs for LobWISE are in the form of whole logs that are harvested from a timber stand by either log type or diameter class (*i.e.*, 13-22 cm, 23-32 cm, 33-47 cm, and 48+ cm), depending on the data available. When size class inputs are used, LobWISE uses regional cull factors (Table A17) developed from US Forest Service Timber Products Output (TPO) data to sort the logs into various types (69). In this study, the silvicultural management comparison used diameter-based inputs. All other inputs were by log type. Log types include pulp logs, chip-n-saw (CNS) logs, saw logs, large saw logs, veneer logs, pole logs, composite logs, and bioenergy logs.

Milling

In the milling process, whole logs undergo a number of transformations to produce primary products. First, inputs are converted into tC. Next, mill residue, including bark, coarse residue (chips, slabs, edgings, trims, cores, etc.), and fine residue (sawdust and shavings) is removed from the log, leaving primary products, according to mill efficiencies for each log type (Table A18). Residue is then used to manufacture wood pellets, otherwise burned or emitted, used for landscaping or animal bedding, used for fiber production (pulp and paper products or non-structural panels), or used for a miscellaneous category. Resulting primary products include softwood lumber, softwood plywood, oriented strand board (OSB), non-structural panels, engineered wood, poles, pulp and paper products, landscaping, animal bedding, and miscellaneous. The breakdown of specific primary products is thus based on the timber product inputs, mill efficiencies, and residue uses. Regional averages are used to determine residue production and use (Tables A19-20). Fossil fuel emissions associated with the procurement of logs, including planting, silviculture, and harvest operations, transportation of logs from the harvest site to the mill, and production of primary products from logs at the mill are also calculated based on the type and amount of primary product produced. These are reported in tCO₂e and are not distinguished

between different greenhouse gases. The fossil fuel emission factors used are based on LCA studies of each product and are based on typical activities for the southern US, according to the respective study authors (*e.g.*, typical silviculture, average distance to mill, etc.) (Table A12). Fossil fuel emissions for post-mill activities (*e.g.*, recycling, construction, post-mill transportation, etc.) are not included.

Manufacturing, Construction, and Use

Primary products are sorted into secondary products based on national consumption averages. Secondary products include new single family homes, new multi-family homes, new manufactured homes, single family home upkeep, multi-family home upkeep, manufactured home upkeep, new buildings, other new structures, other construction (*i.e.*, building upkeep, etc.), shipping pallets, other shipping, utility poles, posts and pilings, animal bedding, landscaping, corrugated boxes, sanitary products, packaging cartonboard, disposable food related products, miscellaneous paper products, furniture, other manufacturing, and miscellaneous (see Supplementary Material for descriptions). A portion of secondary product carbon for certain products is transitioned out of use in year 0, according to waste deduction parameters. The construction waste deduction (5.6%) applies to new residential construction, residential repair, new non-residential construction, and other construction (57,70,71). The manufacturing waste deduction (8%) applies to shipping pallets, other shipping, posts and pilings, furniture, other manufacturing, and miscellaneous (56). After year 0, the remaining secondary product carbon transitions out of use according to Weibull distribution functions (Equation 1). The functions use 2.63 as a shape factor (k) and estimated modes unique to each product according to the literature to calculate the scale factor (λ) (Equation 2) (72).

$$f(x) = C - C \left(1 - e^{-(x/\lambda)^k} \right) \quad (1)$$

$$\lambda = \frac{\text{mode}}{\left(1 - \frac{1}{k} \right)^{\frac{1}{k}}} \quad (2)$$

where C is the carbon in products that enter the market, x is the time since harvest in years, k is the shape factor, λ is the scale factor, mode is an approximation of the product's lifespan, and $f(x)$ is

the carbon remaining in use at year x . Typically, transition distributions in *ex situ* carbon models are based on a first order decay function. However, there is no consensus suggesting that this distribution is best suited to model product transitions out of use, and other models, including Weibull, lognormal, gamma, and Gompertz have been suggested as possible alternatives (73,74). A well-suited distribution should result in slow transition during the earlier years, the majority of the transition close to some estimated lifespan for the product, and transition in the later years that resembles a first order decay curve (74).

Carbon that is sorted into new single and multi-family homes transitions according to specific applications within the home (*e.g.*, floors, walls, doors, etc.) and type of primary product, rather than the home as a whole. All other secondary products transition according to the lifespan of the secondary product, regardless of its different pieces or product makeup.

Recycling, Downcycling, and Landfilling

When carbon transitions out of its first use, it is either recycled, downcycled, landfilled, or emitted. Shipping pallets and all paper products can be recycled within the framework, though the default values within LobWISE assume no recycling of sanitary products or disposable food related products (75). An individual paper product can only be recycled as the same product. For example, packaging cartonboard can be recycled as packaging cartonboard but not as corrugated boxes. This structure is not realistic, as some types of paper are more likely to be made from recycled material than others, but building a network of recycling exchanges would be very challenging given the complexity of the paper recycling product flow and lack of data. Furthermore, landfilling, recycling, and incineration rates are typically available only on the basis of all waste entering the waste stream and do not differentiate newer products from products that can no longer be recycled (75). Within this framework, these generalized rates potentially overestimate emissions from wood products in the first few years and underestimate storage and emissions from landfills in later years. Pallets and paper products are recycled a limited number of times. Carbon that transitioned out of use due to construction and manufacturing waste are not recycled. The framework is structured such that all products can be downcycled as landscaping, animal bedding, posts and pilings, furniture, and other manufacturing, according to national averages, though default values within LobWISE include downcycling only for construction products, shipping products, and utility

poles. Products are landfilled according to national averages in either municipal solid waste (MSW) landfills or construction and demolition (C&D) landfills. A portion of carbon in landfills decays according to a first order decay function with half-lives for a solid wood product category and a paper product category (Equation 3).

$$f(x) = \sum_i \left(C_i \times DOC_f \times e^{\left(-x \left(\frac{\ln(2)}{k}\right)\right)} + C_i \times (1 - DOC_f) \right) \quad (3)$$

where C_i is the carbon that enters a landfill in year i , DOC_f is the fraction of carbon in the product that can decay over time, x is the time since the product was landfilled in years, k is the half-life of the product in a landfill, and $f(x)$ is the carbon remaining stored in a landfill at time x .

Emission

As products transition out of use, product carbon that is not recycled, downcycled, or landfilled is assumed to be emitted as biogenic CO₂. Product carbon is also emitted as biogenic CO₂ as landfilled products decay. Methane produced by decaying products in landfills that is not captured or oxidized is emitted as biogenic methane. CO₂ and methane emissions are reported in tCO₂e. No distinction is made between biogenic carbon emitted with and without energy capture (*i.e.*, only scope 1 emissions). Lag time, sometimes used in landfill modeling to account for the time between product disposal and the time at which conditions are suitable for methane production (15), is assumed to be 0 years (63).

2.2.2 Sensitivity Analysis

LobWISE incorporates over 600 parameters, ranging in certainty from fairly high to very low. We conducted a sensitivity analysis to examine which parameters have the greatest leverage on model outputs to provide insight into the real-world factors that have the most effect on the climate impact of wood products. The sensitivity analysis can also help to identify those factors with low certainty and high influence, about which further scientific research would provide the most benefit. Parameters that were expected to have meaningful leverage on model outputs were tested, with the exception of parameters related to market conditions and consumer patterns (*i.e.*, log type mix and end use category for primary products), as these tests are better suited for an economic analysis.

The sensitivity analysis method used is the Morris method (76), a method of global sensitivity analysis that uses a design of experiments approach to calculate the elementary effect of each input parameter on the model output. This method is computationally frugal, making it suitable for models with slow run time or many parameters, and is appropriate for Excel-based life cycle models (77). In this method, sample parameter sets are randomly generated based on value bounds specific to each parameter. The results indices are μ , μ^* , and σ . The μ index represents the mean elementary effect of an individual input parameter and indicates the overall influence of the parameter on the model output. The μ^* index represents the mean of the absolute values of the elementary effects and indicates both the direct effects of an input parameter and the effects of interactions with other input parameters on the model output. When $\mu \sim \mu^*$, the parameter has a linear positive effect on the model output. When $\mu \sim -\mu^*$, the parameter has a linear negative effect on the model output. The σ index represents the standard deviation of the elementary effects and indicates the level of interaction between the parameter and other parameters. When $|\mu| \neq \mu^*$ or σ is not negligible compared to μ^* , then either the effect of the parameter is nonlinear or there are interactions between the parameter and other parameters (78,79). A list of all parameters tested and their value bounds is provided in the Supplementary Material (Table A36). For most parameters, value bounds were $\pm 10\%$ of the default value for parameters with high certainty and $\pm 20\%$ of the default value for parameters with low and moderate certainty. High certainty is defined as having similar values for the specific parameter that were empirically derived in one or more studies or from published data. Moderate certainty is defined as having similar numbers for a related or generalized parameter that were empirically derived from one or more studies or from published data, or the specific parameter was cited in multiple studies but was not empirically derived. Low certainty is defined as having a related or generalized parameter that was cited in one or more studies but not empirically derived, the specific parameter was cited in only one study and not empirically derived, or information on the parameter is unavailable and based on the professional judgement of the authors. Some parameters had different adjustments based on unique situations (*e.g.*, to capture the range of estimates for the lifespan of paper products present in the literature, the lifespan of paper products was decreased by 50% and increased by 200%). The programming software, Python 3.11.1, was used to generate the sample sets, interact with LobWISE to run each sample set and collect outputs, and analyze the outputs. Each parameter was discretized into 10 levels, and the number of approaches for each parameter was set to 30 (77).

For each sample set, emission pulses from each year, including both biogenic and fossil fuel emissions, were discounted back to year 0 at a 3% rate (80), such that a change in carbon at year 100 was less significant than an equivalent change at year 10 (Equation 4).

$$GHG_{PV} = \frac{GHG_{FV}}{(1+r)^x} \quad (4)$$

where GHG_{FV} is the future value of the GHG pulse emission in year x , r is the discount rate, x is the time since harvest in years, and GHG_{PV} is the present value of the GHG pulse emission in year x . Discount rates represent the heightened value that society places on emissions avoided today rather than tomorrow because of the compounding damage that results the longer atmospheric GHG levels are not reduced, the current cost of GHG emissions to society (*i.e.*, social cost of carbon), and the potential for technology and policy improvements that lower GHG emissions to be implemented in the future. This methodology also reduces the effect of an arbitrary end year on the results of carbon impact comparisons (17,49,81). It is particularly important to consider the time value of carbon within the context of forest systems because of the temporal trade-offs associated with changing annual growth rates and the longevity of HWP carbon. The sum of all discounted emission pulses was used as the model output for the sensitivity analysis. GHG emissions, rather than carbon storage, were used as the collected output because the interest of the analysis was climate impact, and, ultimately, it is the radiative forcing effect of increasing atmospheric levels of GHGs that cause atmospheric warming. To fully capture the temporal effects of emission pulses, dynamic carbon accounting should be used to decay pulse emissions over time and observe the cumulative radiative forcing effects of each GHG (26). However, dynamic accounting is beyond the scope of this study, and we believe emission pulse sums to be a sufficient metric for this analysis. The inputs used for the analysis were loblolly and shortleaf pine timber production across the southern US from 2020, as reported in TPO data (Figure 2.2) (69). Shortleaf pine was included because loblolly and shortleaf pine are reported as a single species category in TPO harvest data. Saw logs were assumed to be 45% CNS logs, 45% saw logs, and 10% large saw logs (82).

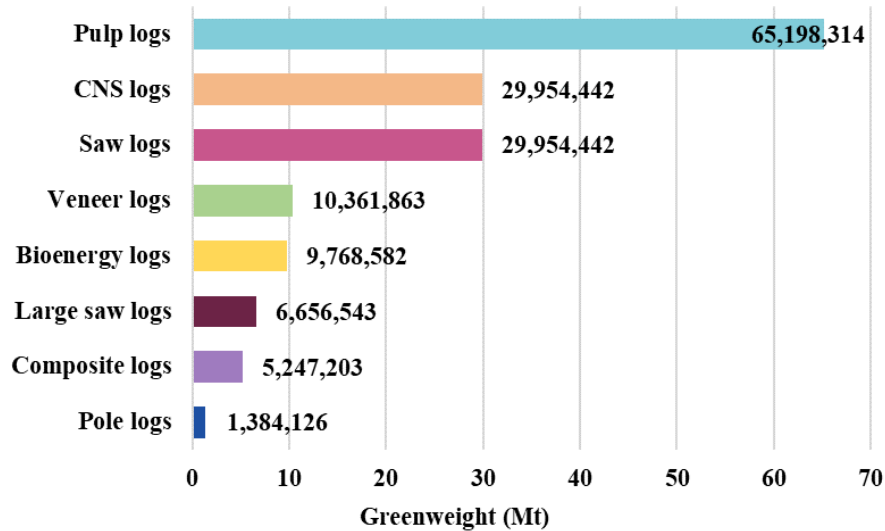


Figure 2.2. Southwide loblolly and shortleaf pine timber production from 2020. Adapted from (69).

2.2.3 Silvicultural Management Scenarios

Table 2.1. Silvicultural management scenarios.

| Scenario | Site Index (SI) (m) | Rotation Length (years) | Thinning |
|---|------------------------|----------------------------|--------------|
| S1. Low productivity pulp (Pulp-20) | 20 | 20 | no thin |
| S2. Low productivity sawtimber (ST-20) | 20 | 30 | thin, age 15 |
| S3. High productivity pulp (Pulp-24) | 24 | 20 | no thin |
| S4. High productivity sawtimber (ST-24) | 24 | 30 | thin, age 15 |

High and low productivity is measured by site index at base age 25; pulp and sawtimber regimes are noted by rotation length.

Four silvicultural management scenarios were analyzed by modeling both *in situ* and *ex situ* carbon storage over 120 years. *In situ* carbon and harvested green weight were modeled with the NC State University-Virginia Tech Forest Productivity Cooperative’s Loblolly Decision Support System (LobDSS v.3.1.0.1), which is the simulator wrapped around the FASTLOB 3.1 growth and yield model (83,84). LobDSS was chosen because it is specific to loblolly pine, and more accurately models green weight than publicly available models, such as PMRC 1996 and PTAEDA (85). The scenarios were designed to represent typical regimes for loblolly pine plantations and included:

(1) a low productivity pulp regime, (2) a low productivity sawtimber regime, (3) a high productivity pulp regime, and (4) a high productivity sawtimber regime (Table 2.1). Shorter rotations (*i.e.*, ~20-25 years) are typically used to produce lower value timber products, such as pulpwood, and longer rotations (*i.e.*, ~25-30 years) are typically used to produce higher value timber products, such as sawtimber. Therefore, we denote the pulp regime by a 20-year rotation and the sawtimber regime by a 30-year rotation (64). Both scenarios for the sawtimber regime included a thin at age 15 down to 16.1 m² of basal area hectare⁻¹. The initial planting density used for all scenarios was 1236 trees hectare⁻¹. Productivity was modeled by changing site index, which is a measure of the height of dominant and co-dominant trees at a given base age (*i.e.*, 25 years). No fertilizer or herbicide applications were simulated.

The *in situ* carbon pools modeled included crop tree stems, branches, foliage, coarse roots, fine roots, and coarse woody debris. Soil and forest floor carbon was assumed to be constant between the management scenarios (86–88). Carbon in non-crop tree vegetation is outside the scope of LobDSS, though this pool may be somewhat constant between management scenarios since herbicide use was not modeled. All root, harvest residue, and coarse woody debris carbon was considered to be emitted in the year of final harvest. Because the outputs generated by LobDSS are in terms of tons of logs per size class, regional cull factors for each size class were used to convert size class tonnage to log type tonnage (Table A17). To account for the varying levels of fossil fuel emissions from procurement, transportation, and production that occur from different log type mixes, the amount of GHG remaining in the atmosphere after the initial pulse emission in the harvest year was calculated according to the revised version of the Bern carbon cycle model, as reported in the 5th Assessment Report of the IPCC (Equation 5) (89).

$$C_{CO_2}(t) = a_0 + \sum_k a_k e^{-t/\tau_k} \quad (5)$$

$$a_0 = 0.2173; a_1 = 0.224; a_2 = 0.2824; a_3 = 0.2763; \tau_1 = 394.4 \text{ years}; \tau_2 = 36.54 \text{ years}; \tau_3 = 4.304 \text{ years}$$

where $C_{CO_2}(t)$ is the amount of CO₂ that remains in the atmosphere, t years after harvest. The tC equivalent to this amount was then subtracted from the *ex situ* storage for each year to deduct the fossil fuel emissions from the overall storage produced in the silvicultural management scenario.

Sums of annual storage over 120 years, discounted at 3%, were used to compare scenarios. Undiscounted annual storage values for years 60 and 120 are also provided in the Supplementary Material (Tables A37-38).

2.2.4 Wood Usage Scenarios

Three wood usage scenarios, intended to represent possible real-world shifts in consumer preferences, policy changes, and technological developments, were tested by modifying specific parameters (Table 2.2). The first scenario represents a path in which sawmills prefer smaller diameter logs over larger logs. The breakdown of saw logs was changed from 45% CNS logs, 45% saw logs, and 10% large saw logs to 80% CNS logs, 20% saw logs, and no large saw logs, creating around 7% less lumber and 4.5% more of each saw residue. The lifespan of furniture was decreased to account for more furniture made with non-structural panels. Fossil fuel rates were also increased because rates are based on tonnage of product produced, and it was assumed that smaller logs consumed similar rates of fossil fuels. The second scenario represents a more waste-conscious society, in which products are used for longer and recycled at higher rates and more times. The third scenario represents a policy shift towards wood energy production. The tonnage of non-growing stock timber (tops, limbs, stumps, and cull sections) used for bioenergy was increased by 100%, and the tonnage of growing stock timber used for bioenergy was increased by 600%, with 90% coming from pulp log volume and 10% from saw log volume. These represent the highest increases possible (to the nearest 100%) without increasing total harvest volume or decreasing total log volume (non-growing stock + growing stock) by more than 40% (for pulp logs) and 5% (for saw logs). For simplicity, all tested harvest combinations had the same total tonnage. Sums of annual storage and emission pulses over 120 years, discounted at 3%, were used to compare scenarios. Undiscounted annual storage and emission pulse values are also provided in the Supplementary Material (Tables A41-48).

Table 2.2. Parameters were adjusted to test the relative carbon benefits of three potential wood usage scenarios.

| Scenario | Parameter Name | Adjusted Value of Parameter | % Change | |
|---|--|---|----------|------|
| S1. Timber product transition: smaller logs preferred by sawmills (> CNS) | CNS produced | 53,252,326 t | +78% | |
| | Sawtimber produced | 13,313,081 t | -56% | |
| | Large sawtimber produced | 0 t | -100% | |
| | Furniture lifespan | 10 years | -23% | |
| | Fossil fuel consumption per ton of lumber carbon produced: | | | |
| | Procurement | 0.01986454 | +7% | |
| | Transportation | 0.01793715 | +7% | |
| | Production | 0.09434880 | +7% | |
| | S2. Products are used for longer periods of time and recycled at higher rates (> Lifespan) | All products lifespans (except sanitary products, disposable food related produced, packaging cartonboard, animal bedding, and landscaping) | -- | +10% |
| | | Pallet recycling | | |
| Recycling rate | | 0.8 | +10% | |
| Number of times recycled | | 5 | +2 times | |
| Paper products recycling | | | | |
| Corrugated boxes | | 0.964 | +5% | |
| Sanitary products | | 0 | -- | |
| Packaging cartonboard | | 0.608 | +40% | |
| Disposable food related products | | 0.1 | +10% | |
| Miscellaneous paper products | | 0.181 | +10% | |
| Number of times recycled | | 8 | +3 times | |
| Paper products landfilling | | | | |
| Corrugated boxes | | 0.028 | -- | |
| Sanitary products | | 0.656 | -- | |
| Packaging cartonboard | | 0.24 | -20% | |
| Disposable food related products | | 0.719 | -10% | |
| Miscellaneous paper products | | 0.478 | -10% | |
| C&D waste | | | | |
| Downcycling to non-structural panels | 0.129 | +10% | | |
| Landfilling | 0.622 | -10% | | |
| S3. Use of potential pulpwood for bioenergy production (> Bioenergy) | Pulp logs produced | 39,724,441 t | -39% | |
| | CNS logs produced | 28,680,741 t | -4% | |
| | Sawtimber logs produced | 28,680,741 t | -4% | |
| | Large sawtimber logs produced | 6,373,498 t | -4% | |
| | Veneer logs produced | 10,361,863 t | -- | |
| | Pole logs produced | 1,384,126 t | -- | |
| | Composite logs produced | 5,247,203 t | -- | |
| | Bioenergy logs produced | 38,072,862 t | +290% | |

2.3 Results

2.3.1 LobWISE Results for the Southern US

Estimated HWP Storage and Emissions Across the Southern US from Loblolly and Shortleaf Pine Timber, Based on TPO Harvest Data for 2020

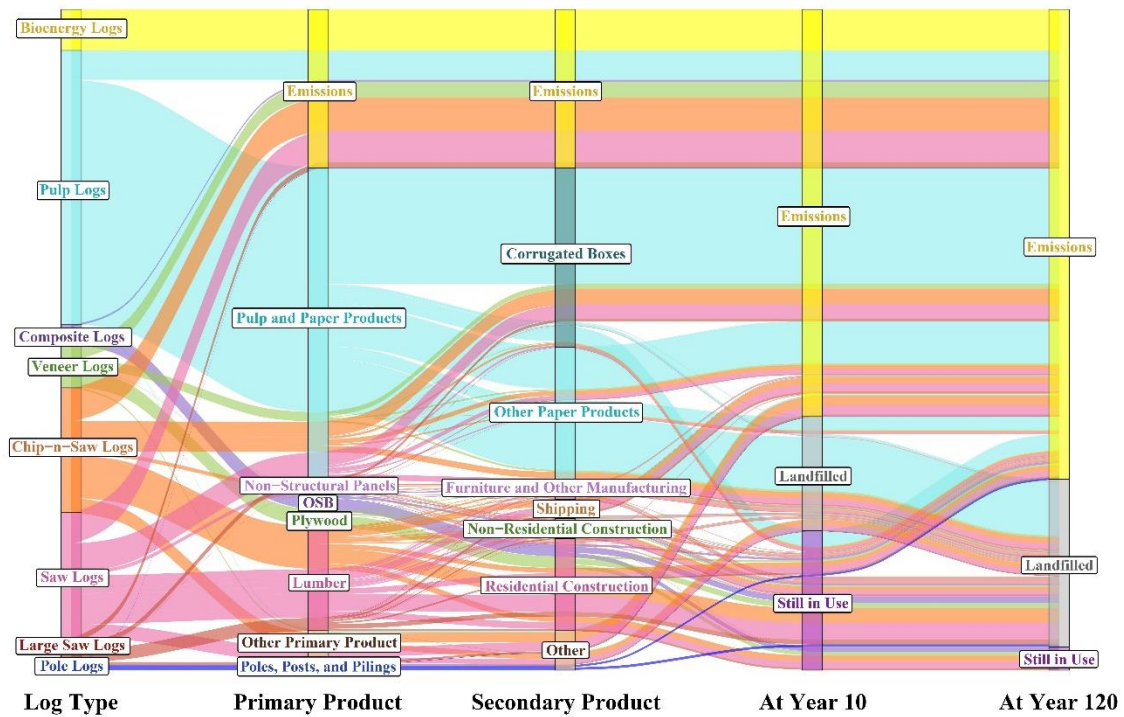


Figure 2.3. The flow of HWP carbon from southwide loblolly and shortleaf pine timber production.

Table 2.3. Stored HWP carbon in use from southwide loblolly and shortleaf timber by sector (MtC).

| Sector | Year 0 | Year 10 | Year 120 | Discounted Sum Over 120 years (3%) |
|------------------------------|--------|---------|----------|------------------------------------|
| Residential construction | 5.5 | 5.4 | 1.4 | 148.4 |
| Non-residential construction | 1.2 | 1.2 | <0.1 | 27.5 |
| Pulp and paper products | 18.9 | 1.3 | 0 | 85.7 |
| Shipping | 1.1 | <0.1 | 0 | 3.9 |
| Manufacturing | 0.8 | 0.3 | <0.1 | 7.6 |
| Other | 2.1 | 0.3 | <0.1 | 12.2 |
| Landfills | 0.1 | 6.7 | 9.9 | 236.4 |

Using TPO harvest data for 2020 as inputs, we estimate that HWPs from loblolly and shortleaf pine timber harvested across the entire southern US store 29.7 MtC in the year they enter the market (year 0), 15.2 MtC after 10 years, and 11.4 MtC after 120 years in use and in landfills (Figure 2.3) (Table A26). Fossil fuel emissions from the procurement, transportation, and manufacturing of these wood products are estimated to be 43.3 MtCO₂e in year 0. We estimate biogenic emissions from burned log carbon (*e.g.*, pellets, residue burned at mills, etc.) in year 0 to be 34.5 MtCO₂e. More carbon went into pulp and paper products than any other category of primary or secondary products (Table 2.3), though much of this carbon was quickly emitted or landfilled. Residential construction and landfills provided the most stable carbon storage over time (Table 2.3). The secondary product categories with the most carbon storage in year 0 were corrugated boxes, sanitary products, single family homes, packaging cartonboard, single family home upkeep, and disposable food related products (Table A28).

Carbon Storage and Emissions by Log Type and Primary Product

Table 2.4. Carbon storage and emission pulses by log type.

| Log Type | Total Storage (tC) | CO ₂ Emissions (biogenic) (tCO ₂ e) | Methane Emissions (biogenic) (tCO ₂ e) | Total Emissions (biogenic + FF) (tCO ₂ e) |
|----------------|-----------------------|---|---|--|
| Pulp logs | 285.4 | -60.1 | -6.4 | -108.9 |
| CNS logs | 359.9 | -53.8 | -2.0 | -73.4 |
| Saw logs | 381.7 | -51.6 | -2.0 | -70.7 |
| Large saw logs | 425.3 | -47.2 | -1.8 | -65.4 |
| Veneer logs | 392.6 | -50.2 | -1.9 | -74.6 |
| Pole logs | 587.0 | -56.4 | -1.1 | -68.1 |
| Composite logs | 681.7 | -20.2 | -0.8 | -41.4 |
| Bioenergy logs | 0.3 | -91.8 | 0.0 | -98.9 |

Sum of stored carbon (in use and in landfills) and GHG emission pulses from 100 green tonnes of timber over 120 years, discounted at 3%; FF = fossil fuel.

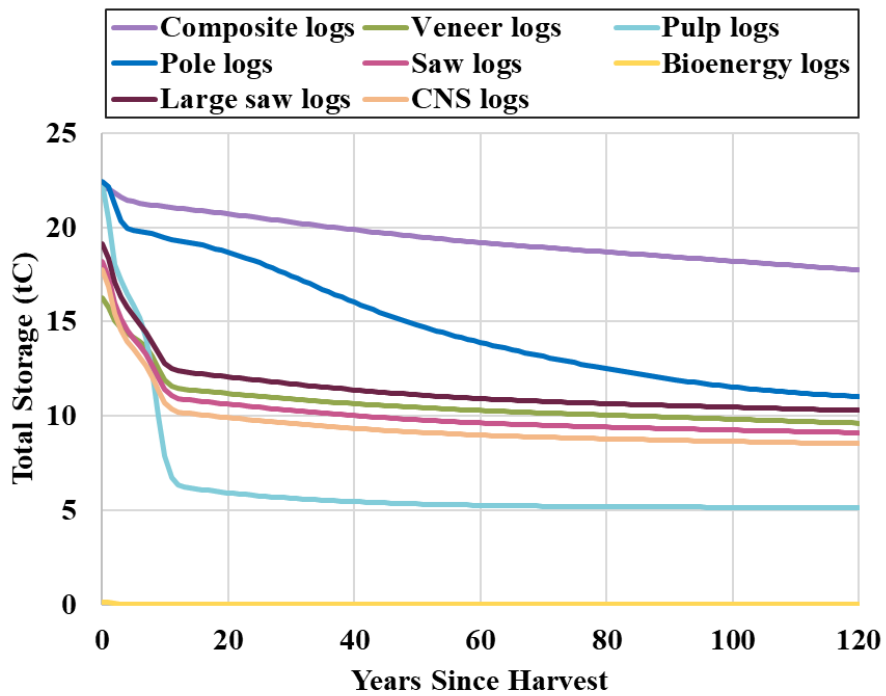


Figure 2.4. Total carbon storage (in use and in landfills) from 100 green tonnes of logs.

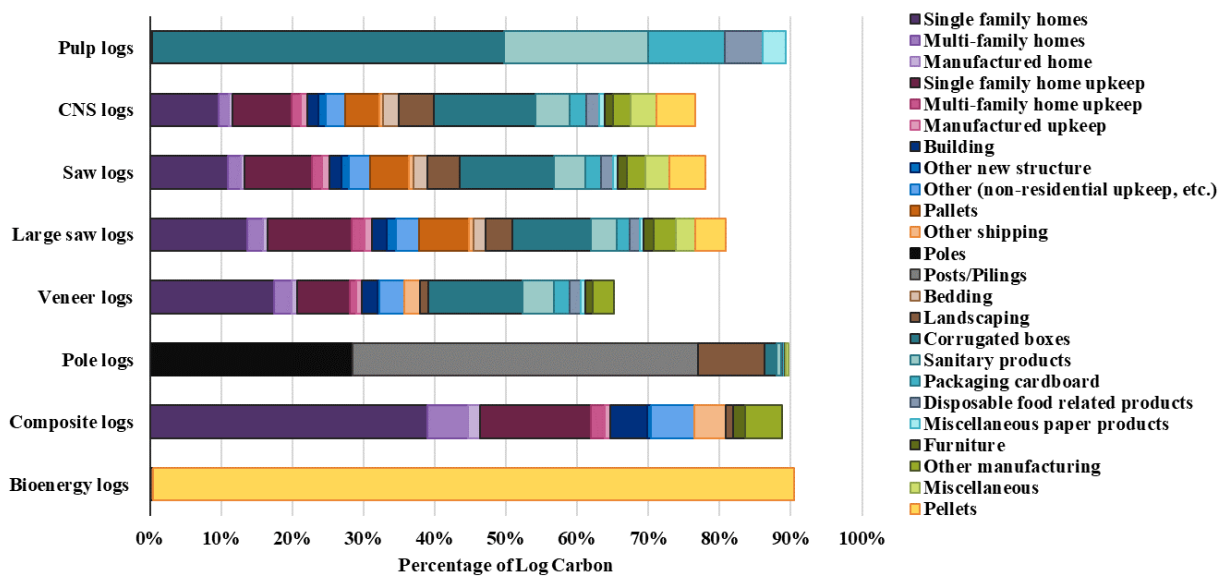


Figure 2.5. Percentage of carbon from harvested loblolly pine logs in secondary products by log type.

Storage and emissions sums for each log type show that pulp logs have the greatest total emissions while composite logs, which are used to manufacture OSB and make up around 3% of southwide loblolly and shortleaf timber production, have the least (Table 2.4). Composite logs also store the most carbon compared to other log types per 100 green tonnes (Figure 2.4; Table A29). The advantage of composite logs can be attributed mainly to higher mill efficiency (35-50% for saw logs v. 90% for composite logs), resulting in a higher portion of saw log carbon that is burned in year 0 (21-27% v. 8%) or used for pulp and paper production (19-24% v. <1%) (Figure 2.5). OSB is used more commonly in longer-lasting products than lumber (*e.g.*, 48.5% of OSB is used in new residential construction v. 31.7% of lumber), but the similar shape of the carbon storage curves after year 20 suggests that the secondary product mix is less important than mill efficiency and primary product mix. All solid wood primary products provided relatively stable carbon storage over time (Table 2.5). Engineered wood provided the most stable carbon storage due primarily to its high usage in new residential construction (80%), though this parameter value was based solely on the professional judgement of the authors. The portion of carbon remaining in other primary products, including lumber, plywood, OSB, non-structural panels, and pulp and paper, can be considered more certain.

Table 2.5. Portion of primary product carbon remaining in use and in landfills in year 100.

| Ranking | In Use | In Landfills | Total | Smith et al. Estimation (Total) |
|-------------------------|---------------|---------------------|--------------|--|
| Lumber | 0.184 | 0.470 | 0.654 | 0.639 |
| Plywood | 0.307 | 0.492 | 0.798 | 0.645 |
| OSB | 0.306 | 0.493 | 0.798 | 0.696 |
| Non-structural panels | 0.009 | 0.703 | 0.712 | 0.592 |
| Engineered wood | 0.487 | 0.377 | 0.862 | --- |
| Poles | 0.082 | 0.509 | 0.555 | --- |
| Pulp and paper | 0.000 | 0.228 | 0.228 | 0.151 |
| Landscaping and bedding | 0.000 | 0.131 | 0.131 | --- |
| Miscellaneous | 0.000 | 0.718 | 0.718 | 0.521 |

Estimates from Smith et al. (57), one of the most commonly cited wood product carbon studies (53,56,59,62,64,90–93), are provided for comparison. Portions from year 100 are presented to match the timeframe of Smith et al. Estimates up to year 120 are provided in the Supplementary Material (Tables A33-35).

2.3.2 Sensitivity Analysis

Table 2.6. Sensitivity of emissions from loblolly and shortleaf pine wood products to the most influential parameters.

| Ranking | Parameter | Bounds | Units | μ | μ^* |
|---------|---|-----------------|--|--------|---------|
| 1 | DOC_f for paper in MSW landfills | 0.25 - 0.93 | portion | -16.68 | 16.68 |
| 2 | portion of CH ₄ recovered (R) in MSW landfills | 0.4019 - 0.8019 | portion | 9.62 | 9.62 |
| 3 | lifespan of corrugated boxes | 0.5 - 3 | years | 8.29 | 8.29 |
| 4 | downcycling to non-structural manufacturing of C&D waste | 0 - 0.129 | portion | -4.84 | 4.84 |
| 5 | production FF for pulp and paper | 0.3746 - 0.4579 | tCO ₂ e emitted/ tCO ₂ e in product | -4.81 | 4.81 |
| 6 | portion of CH ₄ oxidized (OX) in MSW landfills | 0.0221 - 0.4221 | portion | 4.73 | 4.73 |
| 7 | average sawmill efficiency | 0.3 - 0.5 | portion | 4.45 | 4.45 |
| 8 | DOC_f for wood in C&D landfills | 0 - 0.5 | portion | -4.19 | 4.19 |
| 9 | recycling rate for corrugated boxes | 0.814 - 1 | portion | 3.98 | 3.98 |
| 10 | recycling times for corrugated boxes | 3 - 7 | times | 3.97 | 3.97 |
| 11 | lifespan of single family home upkeep | 12 - 62 | years | 2.77 | 2.77 |
| 12 | pulp mill efficiency | 0.79 - 0.99 | portion | -2.68 | 2.68 |
| 13 | construction waste | 0 - 0.156 | portion | -2.61 | 2.61 |
| 14 | DOC_f for wood in MSW landfills | 0 - 0.5 | portion | -2.49 | 2.49 |
| 15 | half-life of landfilled paper | 12 - 18 | years | 2.4 | 2.4 |

DOC_f = the fraction of landfilled organic carbon that will decay over time; MSW = municipal solid waste; C&D = construction and demolition; average sawmill efficiency = sawmill efficiency for 33-47 cm saw logs, with smaller logs having -0.05 efficiency and larger logs having +0.1 efficiency; the magnitude of μ^* indicates the influence of the parameter; the sign of μ indicates the direction of the effect; the bounds indicate the tested range of parameter values (see section 2.3); the model output of which sensitivity was evaluated was the total (biogenic + fossil fuel) annual emission pulses from southwide loblolly and shortleaf pine harvested wood products produced over 120 years, discounted at 3%; a table of all parameters tested and their sensitivity indices is available in the Supplementary Material (Table A36).

The results of the sensitivity analysis indicate relatively high influence for parameters related to short-lived products and landfills, including the fraction of organic carbon that decays in landfills, the portion of methane from MSW landfills that is oxidized and recovered, and parameters related to all life stages of corrugated boxes, including production, lifespan, recycling, and landfill decay

(Table 2.6). Other influential parameters included those related to C&D waste, milling efficiency, and the lifespan of single family home upkeep and repair products. We estimate that total landfill emissions (CO_2 + methane) account for around 9% of all discounted (3% rate) biogenic and fossil fuel emissions from loblolly and shortleaf pine harvested wood products over 120 years, and methane emissions from landfills account for around 4% (tCO_2e). Though these percentages are relatively small, most of the parameters related to landfills within the proposed framework are for large categories of carbon (*e.g.*, all landfilled solid wood products or all wood products in MSW landfills), intensifying the influence of these parameters compared to parameters that are specific to secondary or primary product categories.

A positive μ value generated by the sensitivity analysis indicates that increasing the value of the parameter will generate fewer emissions, and thus have climate benefits. For example, extending the lifespan of corrugated boxes or the half-life of landfilled paper products will have climate benefits. Conversely, a negative μ value indicates that decreasing the value of the parameter will have climate benefits. For example, decreasing the fraction of organic carbon that decays in landfills or lowering fossil fuel emission rates from pulp and paper production will have climate benefits. Interestingly, the results indicate that downcycling less C&D waste into manufacturing products (*i.e.*, furniture and other manufacturing products) would result in climate benefits. This is likely due in part to the relatively short lifespans (7 and 13 years) of manufacturing products. However, because the samples are generated randomly within the Morris method global sensitivity analysis, the rates of other fates of C&D products (*i.e.*, landfilled, downcycled to landscaping, and emitted) that were tested alongside fluctuating rates of downcycling to manufacturing are uncertain, and further analysis is required to analyze the interactions between these parameters.

2.3.3 Silvicultural Management Scenarios

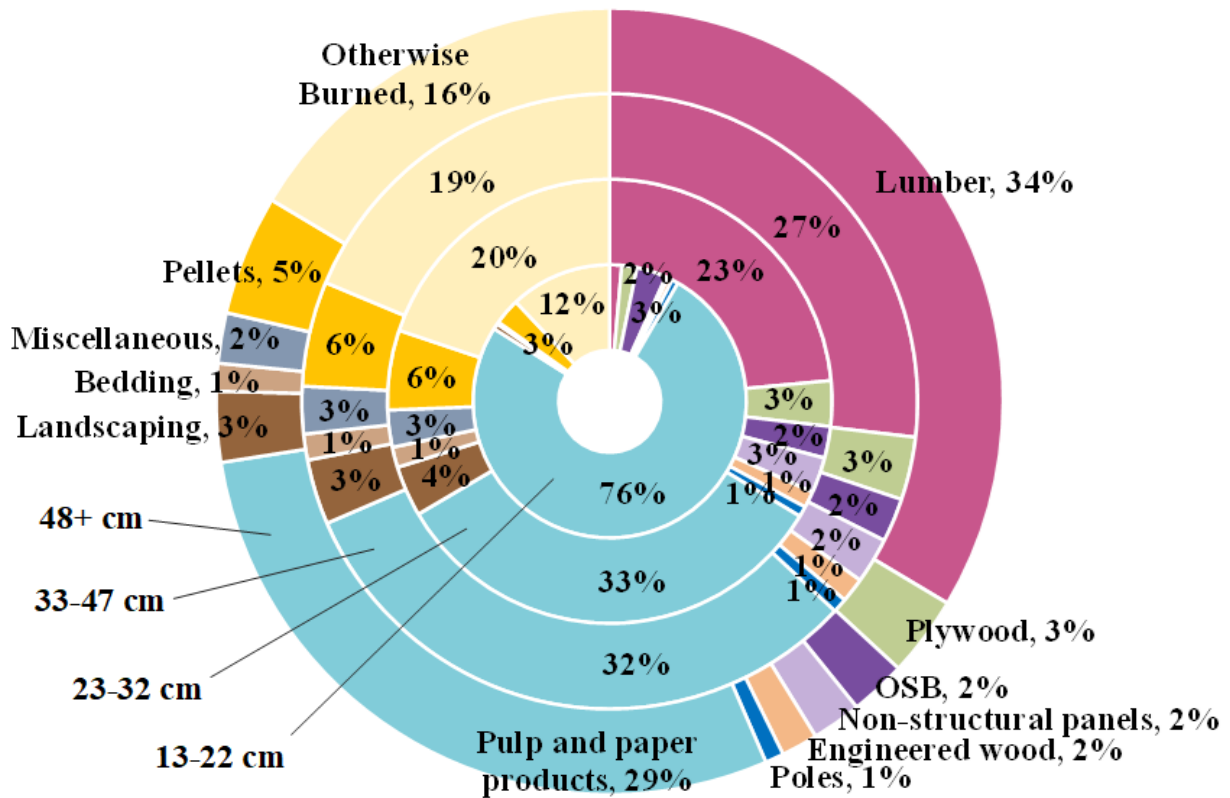


Figure 2.6. Percentage of harvested loblolly pine log carbon in primary products by diameter at breast height (DBH).

Because LobDSS generates outputs in terms of tons of logs per size class, regional cull factors were used to convert size classes into log types (Table A17). After accounting for cull factors and mill residue use, 13-22 cm DBH logs had the highest portion of carbon enter the market as non-energy products, followed by 48+ cm DBH logs (Figure 2.6).

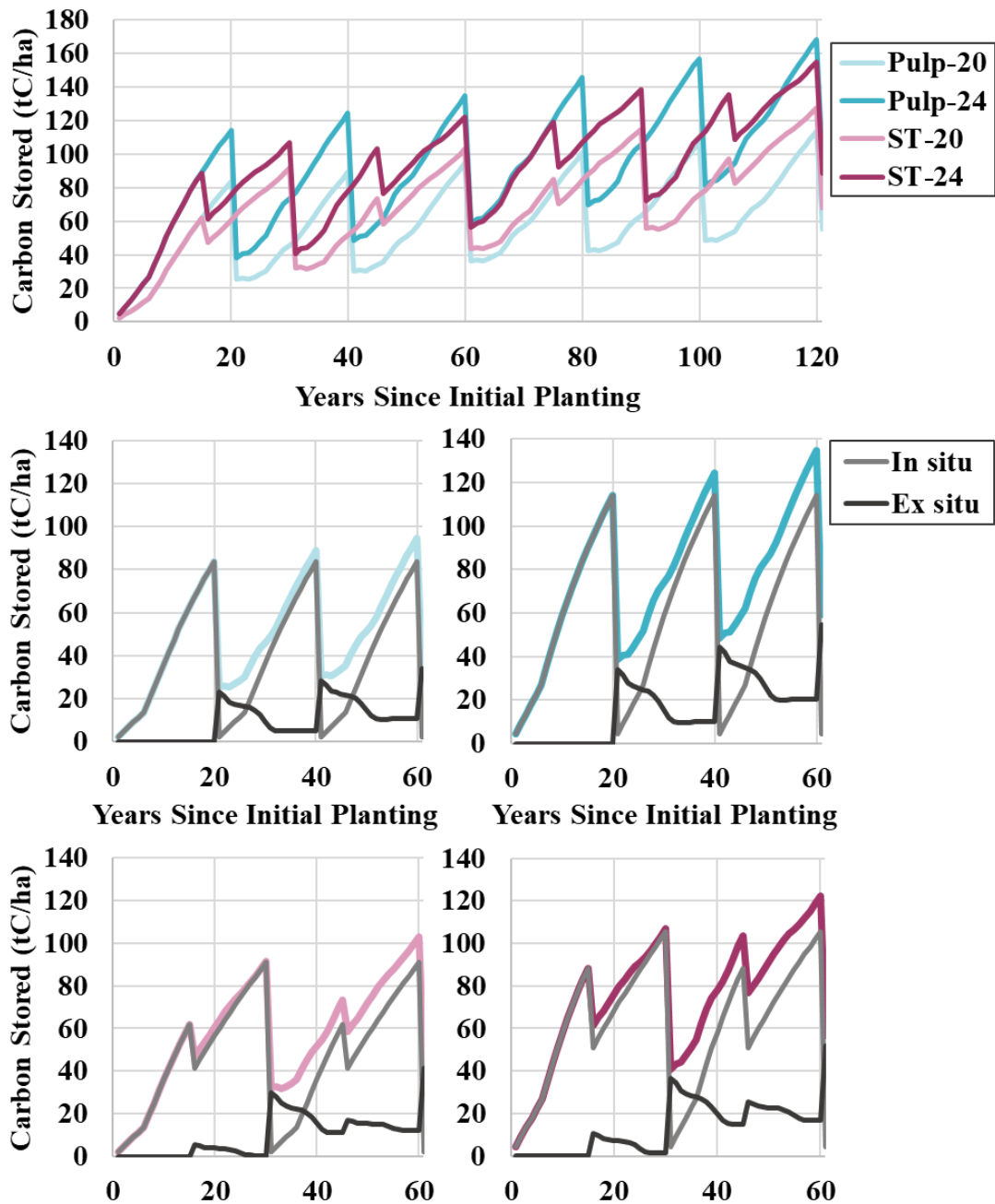


Figure 2.7. Total (colored), *in situ* (gray), and *ex situ* (black) carbon storage. (a) Four silvicultural management scenarios, (b) Pulp-20 (20-year rotation with SI-20 m), (c) Pulp-24 (20-year rotation with SI-24 m), (d) ST-20 (30-year rotation with SI-20 m), (e) ST-24 (30-year rotation with SI-24 m); (SI = site index for base age 25).

Our results show that on low productivity sites, the sawtimber regime stored more total carbon (*in situ* + *ex situ*) over 120 years (1649 tC ha⁻¹) than the pulp regime (1449 tC ha⁻¹) at a 3% discount rate. For high productivity sites, however, the pulp regime stored slightly more total carbon (2246 tC ha⁻¹) than the sawtimber regime (2227 tC ha⁻¹) (Figure 2.7). *In situ* carbon storage was higher in the high productivity sites and sawtimber regimes, and *ex situ* carbon storage was higher in the high productivity sites and pulp regimes, as was total harvest tonnage (Table 2.7). Between the high productivity sites, the sawtimber regime produced slightly more lumber and substantially less pulp and paper over 120 years, compared to the pulp regime (Table A39). While the portion of carbon that entered the market as longer-lived products increased for the sawtimber regimes compared to the pulp regimes on a per harvest basis, the high productivity pulp regime produced the highest total amount of carbon in longer-lived products over 120 years (Table A40). In all scenarios, more carbon was used for corrugated boxes than any other secondary product, with corrugated boxes accounting for between 37% and 43% of all carbon that entered the market over 120 years (Table A40). In all scenarios, *ex situ* storage accumulated over each rotation.

Table 2.7. Total harvested log tonnage over 120 years for four silvicultural management scenarios.

| Scenario | Pulp-20 | Pulp-24 | ST-20 | ST-24 |
|---------------------|----------------|----------------|--------------|--------------|
| 13-22 cm logs (DBH) | 781 | 854 | 510 | 643 |
| 23-32 cm logs (DBH) | 437 | 903 | 576 | 649 |
| 33-47 cm logs (DBH) | 0 | 12 | 112 | 264 |
| Total | 1,218 | 1,769 | 1,198 | 1,556 |

DBH = diameter at breast height; 0% discount rate for harvest tonnage; values are in tonnes green weight hectare⁻¹.

2.3.4 Wood Usage Scenarios

Table 2.8. Difference (Δ) in stored carbon and GHG emission pulses between BAU and wood usage scenarios.

| Scenario Scenario No. | BAU | >CNS (S1) | >Lifespans (S2) | > Bioenergy (S3) |
|---|--------|--------------|--------------------|---------------------|
| Storage in use (MtC) | 285.3 | -8.2 | +55.8 | -32.2 |
| Storage in landfill (MtC) | 236.4 | +0.2 | -34.0 | -51.1 |
| Total storage (MtC) | 521.1 | -8.0 | +20.6 | -83.3 |
| Biogenic CO ₂ emission pulses from products (MtCO _{2e}) | -87.2 | +0.7 | +3.2 | +10.0 |
| Biogenic CO ₂ emission pulses from landfills (MtCO _{2e}) | -2.7 | +0 – 0.1 | -0.5 | -0.8 |
| Biogenic CH ₄ emission pulses from landfills (MtCO _{2e}) | -5.8 | +0 – 0.1 | -1.1 | -1.7 |
| Fossil fuel emissions (MtCO _{2e}) | -43.3 | +0.3 | 0 | -9.2 |
| Total emissions (MtCO _{2e}) | -139.0 | +1.1 | +1.6 | -1.8 |

BAU = business as usual; CNS = chip-n-saw; BAU values are sums of annual storage or emission pulse values over 120 years, assuming the default parameter values for LobWISE, discounted at 3%; values presented for S1, S2, and S3 (right side columns) indicate the change (Δ) in the absolute value of the presented BAU value (*e.g.*, we estimate that storage in use was decreased by 8.2 MtC and CO₂ emissions from products were increased by 0.7 MtCO_{2e} in S1 over 120 years).

Most differences in storage and emission pulses between the wood usage scenarios took place within the first 20 years after harvest (Figure 2.8). With the exception of pellets (+16.0%) and pulp and paper products (-14.7%) in S3, no scenarios generated substantially different primary product mixes from the business as usual (BAU) scenario. S1 showed little change in either storage or emissions (Table 2.8). Product carbon remained in use for a longer period of time in S2, likely primarily due to the increased lifespan and recycling of corrugated boxes. Since less carbon overall entered the market as non-energy products in S3, biogenic emission pulses from products burned and decaying in landfills were 15.2 MtCO_{2e} lower, with the exception of year 0 in which the pellets were burned and biogenic emissions increased by 22.6 MtCO_{2e}. Additionally, while carbon that was diverted to pellets in S3 was emitted as CO₂, a portion of that carbon in the BAU scenario was emitted as methane (5.8 MtCO_{2e}) from products decaying in landfills, resulting in higher biogenic emissions in the BAU scenario from the same amount of log carbon. Fossil fuel emissions were lower in S3 than in the BAU scenario (-9.2 MtCO_{2e}), primarily due to the lower fossil fuel consumption rates associated with pellet production (0.3179 tCO_{2e} emissions/tC product) as compared to pulp and paper production (1.8992 tCO_{2e} emissions/tC product) (73,74).

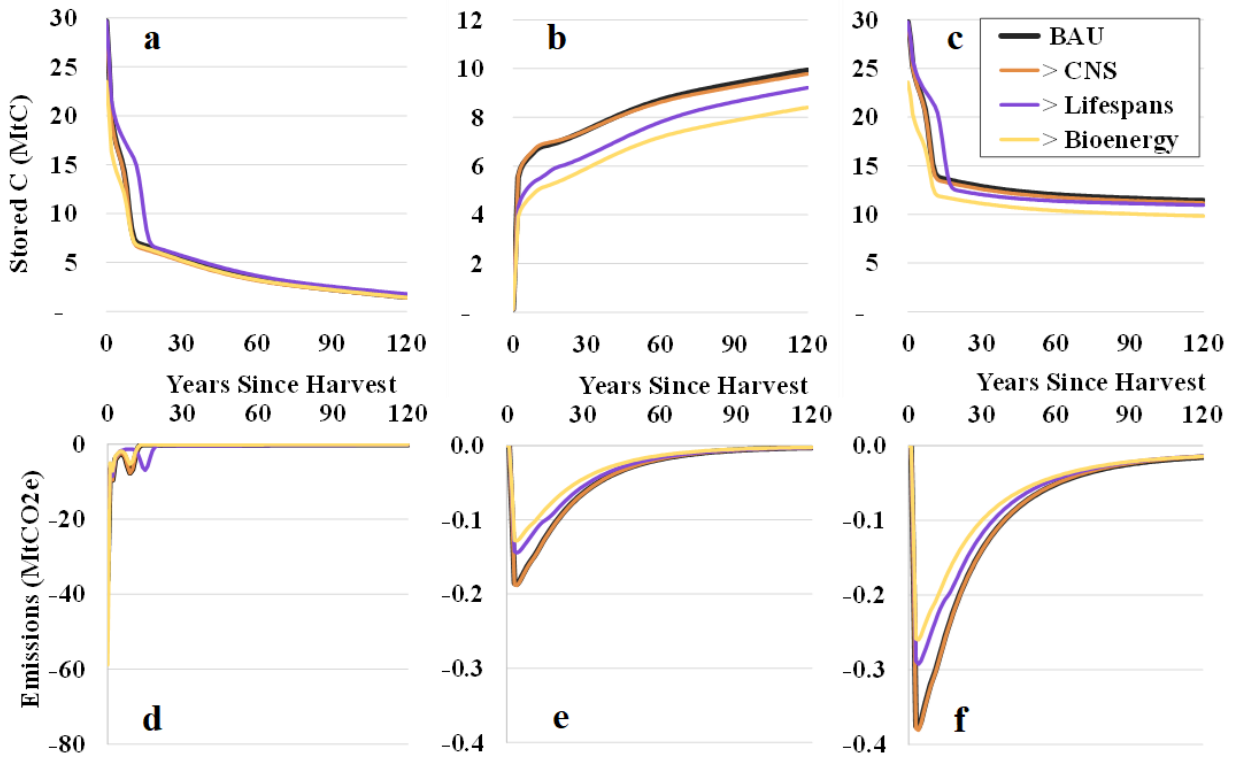


Figure 2.8. For each wood usage scenario: (a) carbon stored in use, (b) carbon stored in landfills, (c) total carbon storage, (d) biogenic CO₂ emission pulses from wood products, (e) biogenic CO₂ emission pulses from landfills, and (f) biogenic methane emission pulses from landfills.

2.4 Discussion

Results from this analysis suggest that the combined carbon storage of pine plantations and resulting HWP have the potential to grow over time, despite the temporary loss of carbon storage on forested stands that results from harvests. Many studies have come to similar conclusions for both southern pine (10,49,94,95) and other forest types (96–98). However, we find that future carbon storage and emissions are sensitive to both silvicultural management and parameters along the wood product flow. Our results suggest that adjusting rotation length based on individual site productivity, as well as extending the storage of carbon in key products, such as corrugated boxes and residential upkeep products, and in landfills could result in substantial carbon gains.

Longer rotations are frequently recommended as a strategy for increasing both *in situ* and *ex situ* carbon in even-aged stands (10,94,99,100) due to the amount of *in situ* carbon that is emitted soon

after each harvest (*i.e.*, slash, roots, competing vegetation) and the higher portion of long rotation harvests that are saw logs, resulting in more long-term *ex situ* storage. Our findings similarly suggest that longer rotations (30 years) may be advantageous when site productivity is low (20 SI vs. 24 SI). However, they also indicate that shorter rotations (20 years) may be advantageous under certain conditions, such as high site productivity, suggesting that landowners hoping to optimize total forest carbon storage should make site specific management decisions, rather than opting for a longer rotation in all cases. Between silvicultural management scenarios with the same rotation lengths, sites with higher productivity had higher total carbon storage. Gonzalez-Benecke et al. (10) similarly found that lowering site index to 15 m from a default of 22 m resulted in 28% less net (*in situ* + *ex situ* – fossil fuel emissions from silviculture) carbon storage for loblolly pine, while increasing site index to 30 m resulted in 38% more storage. This finding suggests possible benefits of using silviculture or genetics to improve site productivity.

We also identify several changes within the wood product flow that could lead to significant carbon gains if realized, including reducing decay from landfills, increasing methane capture and oxidation in MSW landfills, extending the lifespan of corrugated boxes and residential upkeep and repair products, recycling corrugated boxes at a higher rate and more times, increasing the mill efficiency of saw logs, and favoring composite and CNS logs over veneer and higher-diameter saw logs. Despite the importance of landfill decay parameters, such as the fraction of organic carbon in various materials that decays under anaerobic landfill conditions (DOC_f), few studies have quantified these parameters for individual materials (101,102). IPCC guidance recommends a default DOC_f factor of 0.5 for all materials (63), but studies have shown wide ranges in this factor, depending on the material, from 0-3% in solid wood (15) to 93% in copy paper (101). Further scientific research on this topic could benefit GHG emission estimations from landfills and enhance the understanding of wood product carbon flows.

According to our findings, corrugated boxes represent the largest portion of new product carbon from real southern US loblolly and shortleaf harvests, as well as all simulated silvicultural management scenarios. According to the US EPA, corrugated boxes make up 11.4% of all US MSW waste generation, including non-wood materials (75). Most literature surrounding *ex situ* carbon uses 1-3 years as the lifespan for all paper products, including corrugated boxes

(10,37,57,61). The US EPA categorizes corrugated boxes as “containers and packaging,” which are assumed to be discarded in the year they are purchased (103). Corrugated boxes are generally considered to have one of the highest rates of recycling of any material in the US, with rate estimates ranging from 91% (104) to 96% (103). Even with already high rates, we estimate that further improvements in corrugated box recycling would result in substantial carbon gains. Several studies have found that increasing recycling rates of various products, including certain paper products, leads to minimal GHG emission reductions and may even increase GHG emissions due to economic ramifications, causing production of additional primary products, and to additional emissions involved with recycling and product loss during the recycling process (105–107). These contradictory results highlight the complexity of waste systems and the need to incorporate economic responses into future studies.

Results of the sensitivity analysis also indicated sensitivity to mill efficiency for saw and pulp logs. While pulp mill residues are exclusively bark that cannot be made into paper products, residues from saw mills include bark, coarse residue, and fine residue, and are affected by log attributes (diameter, length, taper, defects, etc.), scanning and sawing machinery, and product mix (108). Giasson et al. (109) also found sawmill efficiency to be an important factor in reducing emissions from softwood products. Estimates for sawmill efficiencies range from 36% (69) to 46% (11), and these efficiencies increase over time as sawmill technology develops. Milota et al. (11) surveyed sawmills in the southern US and found that over half of the mills had upgrades to scanning, optimization, grading, or planer systems in the few years preceding the survey. It is assumed in this study that larger logs have higher conversion efficiencies than smaller logs, but the degree to which this is true is not well studied (108). Many contemporary mills retain data on both log characteristics and lumber recovery factors, and these data could potentially be used to analyze the relationship between log attributes and mill efficiency.

Smith et al. (57) is one of the most commonly cited studies for the portion of wood remaining in wood products after a period of time, especially when regional values are used (53,56,59,62,64,90–93). In comparison to estimates from this study, we found carbon remaining in use in year 100 from primary products to be slightly lower, while carbon remaining in landfills and total carbon remaining were slightly higher (Tables A33-35). The most stable primary products were

engineered wood, plywood, and OSB. Since composite logs, which are used to manufacture OSB, have the highest mill efficiency rate (90%) of any non-energy log type, and since composite logs can generally be grown in short rotations, OSB has potential as a more efficient method of carbon storage than similar products, such as plywood. Lumber also provides relatively stable carbon storage, with an estimated 65% remaining stored in year 100 (Smith et al. (57) estimate 64%). CNS logs, much like OSB logs, can be grown more quickly than higher diameter saw logs to produce lumber, and the minimal effects of increased CNS consumption (-8.3 MtC of total storage over 120 years) in the wood usage scenarios (S1) points to another product shift with carbon storage potential.

2.4.1 Limitations and Future Directions

While fossil fuel emissions from silvicultural activities such as planting, fertilizing, applying herbicide, and harvesting are generally considered to be low, compared to the resulting *in situ* storage gains (10), fossil fuel emissions from transportation and especially production of wood products are significant when compared to the carbon benefits of the resulting products (11,60,110–121). We have accounted for fossil fuel emissions in the silvicultural management scenarios by deducting the tC equivalent to the CO₂ remaining in the atmosphere for a given year from the storage in wood products for that year. However, one tC stored in wood products for one year is not equivalent to one tC emitted to the atmosphere, since emitted carbon will continue to have radiative forcing effects on the atmosphere for many years. Rather, emissions should be contrasted to sequestration, which actively pulls carbon out of the atmosphere and thus prevents future radiative forcing effects. Levasseur et al. (26) propose using dynamic carbon accounting to compare each pulse of sequestration and emissions in the year in which they occur. This method can better analyze the temporal tradeoffs that exist in forest and wood product systems and should be incorporated into further analysis.

Furthermore, we do not incorporate any substitution effects from using wood products rather than alternative construction materials (*e.g.*, concrete, steel, etc.) or deriving energy from wood pellets, mill residue, wood waste, or landfill methane rather than from fossil fuels into our analyses or the proposed framework. Quantifying the potential GHG implications of forest-based bioenergy and wood products substitution would require an integrated assessment approach, with coverage of

energy, industry, and construction sectors and a carefully designed counterfactual scenario. Such an analysis could also require a more involved LCA of alternative construction materials that additional wood would replace. While beyond the scope of this analysis, further research is needed to understand the full potential GHG benefits (or costs) of wood product substitution. Despite these limitations, the framework presented in this manuscript provides a detailed tool to support economic or policy analysis on the benefits of wood use over other construction, energy, and related products. Fossil fuel emissions are also not included in the proposed framework for the recycling process, construction, or any other process in a product's lifetime after the mill.

The proposed framework can be used to assess carbon storage in HWPs under various hypothetical scenarios. In most of our analyses, we assumed constant cull factors, tonnage of log types produced, secondary product mix, and total harvest volume for the southern US. However, market and policy conditions that affect forest management, HWP production and consumption, and land use all influence these parameters, and analyses that consider these effects are essential to understanding the total carbon contribution of southern US pine plantations.

Finally, the silvicultural management scenarios represent only four silvicultural management alternatives based on static, modeled *in situ* carbon estimates. Further analysis is needed to understand the effects of other silvicultural decisions, such as herbicide and fertilizer application, variable planting densities, and genetic material; to include carbon pools such as root and harvest residue carbon; to test LobWISE in combination with empirical *in situ* carbon data; to understand the effect that climate change and rising atmospheric CO₂ levels will have on forest carbon sequestration and harvest outputs; and to understand the effects of spatial parameters on total carbon storage.

2.5 Conclusions

This study uses elements of a LCA approach to develop and parameterize a detailed framework that models carbon in wood products sourced from managed loblolly pine plantation systems, which are a critical input to the global forest products sector. We evaluate carbon storage performance of various product allocation and silvicultural management scenarios, as well as parametric sensitivity analysis to understand key drivers of variability in emissions projections.

The framework provides a flexible decision support tool that practitioners can use to evaluate potential emissions implications of both silvicultural and end product allocation decisions, which can support carbon offset project and corporate insetting strategy development, as well as informing policy design around land- and bioproduct-based mitigation strategies.

Our findings also have relevance to the broader scientific literature on wood product carbon storage. Although we do not account for the GHG emissions displacement potential of wood products and bioenergy, our results show lasting GHG benefits from wood products sourced from southern loblolly pine systems. While our methodology differs substantially from Peng et al. (38), our results similarly point to the important role that HWPs play in the long-term GHG emissions profile of the wood products sector.

Also much of the literature surrounding HWP carbon storage is focused on silvicultural management regimes that produce saw logs and on longer-lasting products, such as housing and buildings (34). This focus on longer-lived wood product carbon storage is consistent with research focus on reducing permanence risk of *in situ* forest carbon management or arguing in favor of climate solutions with long-term carbon storage potential (122). This perspective ignores the important potential role of temporary carbon storage benefits of forest management interventions (17,123).

However, our research findings emphasize the need for a better understanding of carbon flows in short-lived products, such as corrugated boxes, and in landfills. Our findings also emphasize the role of chip-n-saw logs as a potential source of lumber that allows for more efficient carbon sequestration and storage without significantly increasing emissions near- and long-term. The proposed framework can also be linked with growth and yield models for further analysis involving optimization of forest management and product allocation strategies for carbon storage and wood product supply.

CHAPTER

----- 3 -----

CLIMATE EFFECTS OF MANAGEMENT IN SOUTHERN US PINE PLANTATIONS

3.1 Introduction

The global economy has become increasingly dependent on activities that emit greenhouse gasses (GHG) to the Earth's atmosphere, contributing significantly to global temperature rise and climate change. 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 (124). The forest sector plays an important role in global 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 (*e.g.*, 31,125,126).

Managed loblolly pine (*Pinus taeda* L.) plantations in the southern US, in particular, offer a unique opportunity for climate change mitigation because of their prevalence and productivity within the southern forest landscape (4). Tian et al. (127) showed that continued investment in pine plantations would help support and enhance the US forest carbon sink over time. Loblolly pine plantations are often intensively managed, and adjustments to management decisions may improve forest carbon and HWP stocks. For example, Bracho et al. (128) found that the application of operational levels of fertilizer increased carbon accumulation in loblolly pine stands under a wide range of climate conditions across the southern US. Gonzalez-Benecke et al. (10) found that when

wood product carbon pools were included, extending rotations in loblolly plantations increased total carbon stocks, though the carbon gain diminished with longer extensions. Other studies have pointed to the complexities of the relationship between carbon sequestration and management. Zhao et al. (9) notes that aboveground carbon accumulation increased with higher planting density in young loblolly stands but was not significantly affected by planting density after age 15. They further reported that site quality significantly affected aboveground carbon stocks in stands younger than 8 and older than 18 and that the relationship between age and management on aboveground carbon stocks likely changes over time. The realization of potential climate benefits from loblolly plantations therefore requires a nuanced understanding of the effects of management on carbon sequestration and net GHG fluxes.

Historically, studies that assess the climate change mitigation potential of management practices on loblolly plantations have used carbon stocks or carbon accumulation (*i.e.*, sequestration) as a proxy for climate effects (10,49,128–130). Although these metrics are relatively easy to measure and model, they do not necessarily capture the full climate effects of a forest system. For example, fossil fuels are emitted in both forest management and HWP production operations (11,111,131), and some HWP carbon may be emitted to the atmosphere as methane (CH₄) if decay occurs in anaerobic landfill conditions (74). When only carbon sequestration or stocks are considered, the effects of non-biogenic and non-CO₂ GHG fluxes will not be accounted for.

Numerous methodologies have been developed to account for non-biogenic and non-CO₂ 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 CO₂ over a given time horizon, typically 100 years (132). 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, it does not allow accounting for temporary carbon storage, such as in HWPs (26,133). The value of temporary carbon storage is highly debated (*e.g.*, 16,19,21). 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 (16,19). 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 (17,18,21,23,24). Accounting methodologies that can appropriately quantify both cumulative GHG emissions and the amount and duration of carbon stored temporarily are needed (20). One such approach is the dynamic life cycle assessment (dynamic LCA) approach, proposed by Levasseur et al. (26), 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 US 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 storage as the performance metric of interest.

3.2 Methods

3.2.1 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 3.1). 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 US at coordinates 31.9°N and 81.7°W. All stands received chemical site preparation, were bedded at planting, and received 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 120 ft² ac⁻¹ and the dominant height was at least 40 ft as is operationally typical in the region. Fertilization was applied the year after thinning and included

200 lb ac⁻¹ of nitrogen and 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 (134).

Table 3.1. Thirty-six management scenarios for loblolly pine plantations were modeled.

| Scenario number | Site index (ft) | Planting density (TPA) | Thinning Regime | Fertilization Regime |
|------------------------|------------------------|-------------------------------|------------------------|-----------------------------|
| S1 | 65 | 400 | Thin, age 15 | Fertilization, age 16 |
| S2 | 65 | 550 | Thin, age 14 | Fertilization, age 15 |
| S3 | 65 | 700 | Thin, age 14 | Fertilization, age 15 |
| S4 | 75 | 400 | Thin, age 13 | Fertilization, age 14 |
| S5 | 75 | 550 | Thin, age 12 | Fertilization, age 13 |
| S6 | 75 | 700 | Thin, age 11 | Fertilization, age 12 |
| S7 | 85 | 400 | Thin, age 11 | Fertilization, age 12 |
| S8 | 85 | 550 | Thin, age 10 | Fertilization, age 11 |
| S9 | 85 | 700 | Thin, age 9 | Fertilization, age 10 |
| S10 | 65 | 400 | Thin, age 15 | No fertilization |
| S11 | 65 | 550 | Thin, age 14 | No fertilization |
| S12 | 65 | 700 | Thin, age 14 | No fertilization |
| S13 | 75 | 400 | Thin, age 13 | No fertilization |
| S14 | 75 | 550 | Thin, age 12 | No fertilization |
| S15 | 75 | 700 | Thin, age 11 | No fertilization |
| S16 | 85 | 400 | Thin, age 11 | No fertilization |
| S17 | 85 | 550 | Thin, age 10 | No fertilization |
| S18 | 85 | 700 | Thin, age 9 | No fertilization |
| S19 | 65 | 400 | No thin | Fertilization, age 16 |
| S20 | 65 | 550 | No thin | Fertilization, age 15 |
| S21 | 65 | 700 | No thin | Fertilization, age 15 |
| S22 | 75 | 400 | No thin | Fertilization, age 14 |
| S23 | 75 | 550 | No thin | Fertilization, age 13 |
| S24 | 75 | 700 | No thin | Fertilization, age 12 |
| S25 | 85 | 400 | No thin | Fertilization, age 12 |
| S26 | 85 | 550 | No thin | Fertilization, age 11 |
| S27 | 85 | 700 | No thin | Fertilization, age 10 |
| S28 | 65 | 400 | No thin | No fertilization |
| S29 | 65 | 550 | No thin | No fertilization |
| S30 | 65 | 700 | No thin | No fertilization |
| S31 | 75 | 400 | No thin | No fertilization |
| S32 | 75 | 550 | No thin | No fertilization |
| S33 | 75 | 700 | No thin | No fertilization |

Table 3.1 (continued).

| | | | | |
|-----|----|-----|---------|------------------|
| S34 | 85 | 400 | No thin | No fertilization |
| S35 | 85 | 550 | No thin | No fertilization |
| S36 | 85 | 700 | No thin | No fertilization |

Site index for base age 25; TPA = trees per acre at planting.

3.2.2 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 (83,84). Biomass outputs were converted to carbon stocks using a coefficient of $0.5 \text{ tC (t biomass)}^{-1}$ 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 (86–88). Because FASTLOB does not provide biomass data for stand ages 1–5, biomass for these ages were 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. (135) (equation 1) and Radtke et al. (136) (equation 2), respectively.

$$CR_{\text{roots}} = CH_{\text{roots}} * e^{-0.0534t} \quad (1)$$

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

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 3.2. 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 to the final harvest (131). N₂O emissions from the denitrification of nitrogen fertilizer were also estimated.

Table 3.2. Emission factors used to calculate GHG emissions from silviculture.

| Emission Source | Emission Factor | Unit | Literature Source |
|----------------------------------|------------------------|---------------------------------|--------------------------|
| Upstream N fertilizer production | 0.00246 | tCO ₂ / lb N | (131) |
| Upstream P fertilizer production | 0.00251 | tCO ₂ / lb P | (131) |
| Upstream seedling production | 2.2E-05 | tCO ₂ / seedling | (137–139) |
| Upstream herbicide production | 0.0095 | tCO ₂ / lb herbicide | (131) |
| Herbicide application | 0.00891 | tCO ₂ / ac | (131) |
| Bedding | 0.05789 | tCO ₂ / ac | (131) |
| Fertilizer application | 0.00891 | tCO ₂ / ac | (131) |
| N denitrification | 7.13E-06 | tN ₂ O / lb N | (140) |
| Harvest | 0.23752 | tCO ₂ / ac | (131) |

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. (130), 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 CO₂ 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 CH₄ 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 included in the manufacturing of the primary product at the mill. 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 (*e.g.*, 141–143). However, estimates of appropriate displacement factors range considerably in the literature (144), 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 (145–147). Therefore, we do not include benefits of substitution in our analysis, so our results will likely underestimate forest climate benefits.

3.2.3 Dynamic LCA Calculations

Net Radiative Forcing

We use the dynamic LCA methodology proposed by Levasseur et al. (26) 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 (89,148). We include CO₂ (equation 3), CH₄, and N₂O emissions (equation 4), and thus, three impulse response functions are calculated:

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

$$a_0 = 0.2173; a_1 = 0.224; a_2 = 0.2824; a_3 = 0.2763; \tau_1 = 394.4 \text{ years}; \tau_2 = 36.54 \text{ years}; \tau_3 = 4.304 \text{ years}$$

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

$$\tau_{CH_4} = 12.4; \tau_{N_2O} = 121$$

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).

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

Finally, for each year, y , $RF_{s,y}$ is the sum of all $RF_{s,i}(t)$ for which $(i + t) = y$ (equation 6). 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.

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

Sources of emissions and sequestration in our study are CO₂ emissions from forest decay, which includes decay of foliage, CWD, and roots, CO₂ emissions from HWPs, CH₄ emissions from HWPs, fossil fuel emissions from production, fossil fuel emissions from silviculture, N₂O 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).

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

Sequestration is thus treated as a negative emission because it reduces the amount of atmospheric CO₂ and therefore has cooling effects on the atmosphere compared to a scenario in which the sequestration does not take place (133). 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 the equations provided in section 2.1.1. 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.

$$netRF_y = \sum_s RF_{s,y} \quad (8)$$

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

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

Carbon Storage

Carbon storage is often used as a proxy for climate benefits in forest management studies, carbon offset projects, and forest carbon policy (*e.g.*, 49,53,130,149). To compare the effect of the metric used (*i.e.*, net radiative forcing *v.* carbon storage) on the results, we calculate a metric similar to $netRF_{avg}$ for carbon storage. C_{avg} can be defined as the average carbon stored each year in *in situ* and *ex situ* pools across the time horizon (equation 10).

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

where C_y is the carbon stored 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 (133,150).

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 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 at a 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” (151). 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 (152).

To apply this landscape approach to our study, for each regime, we conduct the analysis described above for 1000 representative acres which have an approximately uniform age class distribution that is maintained throughout the time horizon. The metrics described above are calculated for all 1000 acres simultaneously, such that they represent the climate effects (*e.g.*, $netRF_{avg}$) or carbon storage (C_{avg}) when a regime is applied consistently across the landscape for the duration of the study time horizon. For acres that are not age 0 in year 0 of the time horizon, it is assumed that the regime has been applied to that acre since its planting. Only carbon from acres 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 Storage

When forests sequester CO₂ from the atmosphere, that CO₂ 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 storage benefits. A portion of the carbon used in HWPs will also be stored permanently in landfills (153). The climate benefit of temporary and permanent carbon storage, $StorBen_y$, can be quantified by calculating the difference between radiative forcing effects of sequestration and biogenic emissions (equation 11). Biogenic emission

sources include CO₂ emissions from forest decay, CO₂ emissions from HWPs, and CH₄ emissions from HWPs.

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

3.3 Results

3.3.1 Overall Carbon Dynamics

Radiative Forcing

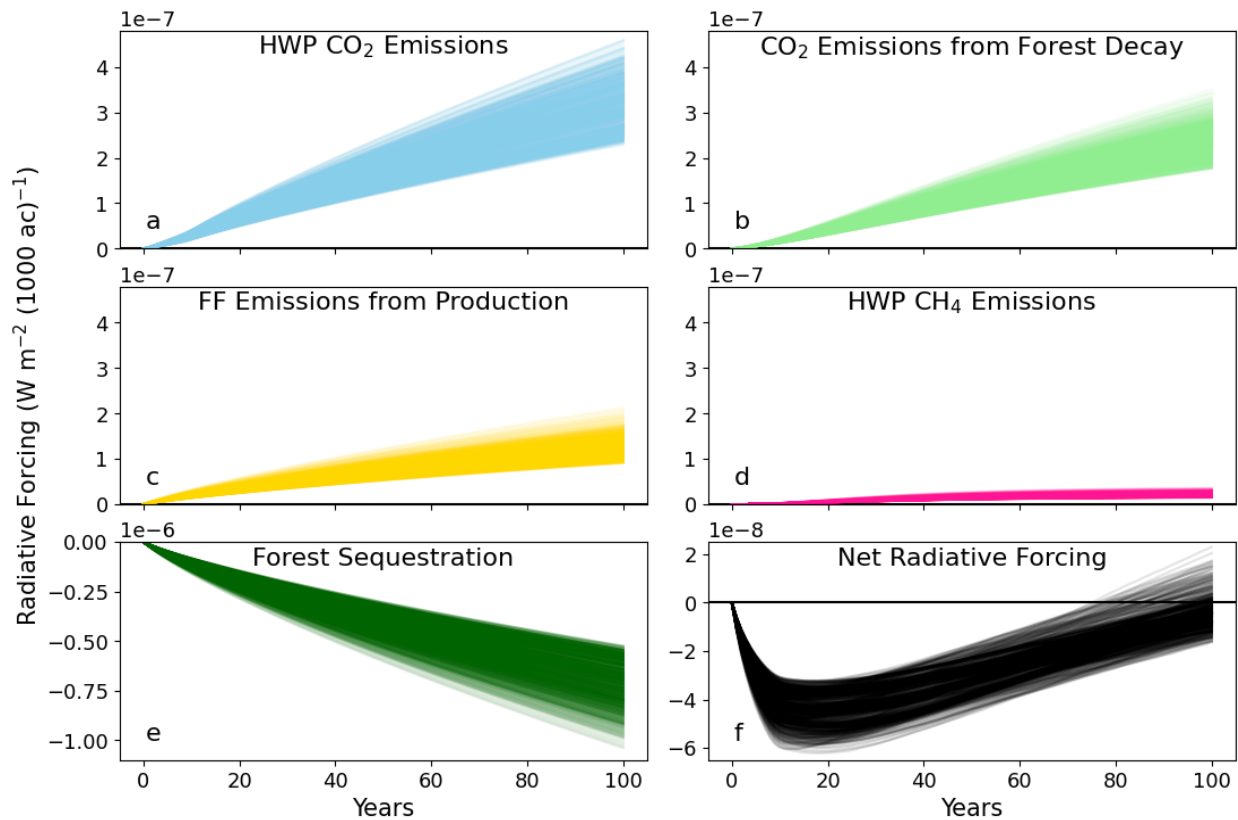


Figure 3.1. Range of (a-e) radiative forcing by source ($RF_{s,y}$) and (f) net radiative forcing ($netRF_y$) for all tested management regimes, applied across a 1000-acre landscape over 100 years.

For all tested regimes, $netRF_{avg}$, which represents the average annual net radiative forcing effect across the time horizon for 1000 acres with the same site quality and forest 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 3.1f). For all regimes, CO₂ emissions from HWPs were the largest source of emissions over 100 years, followed by CO₂ emissions from forest decay, fossil fuel emissions from production, and CH₄ emissions from HWPs (Figure 3.1a-d). Fossil fuel emissions from silviculture and N₂O emissions from fertilizer were very small compared to other emission sources for all regimes.

Carbon Storage

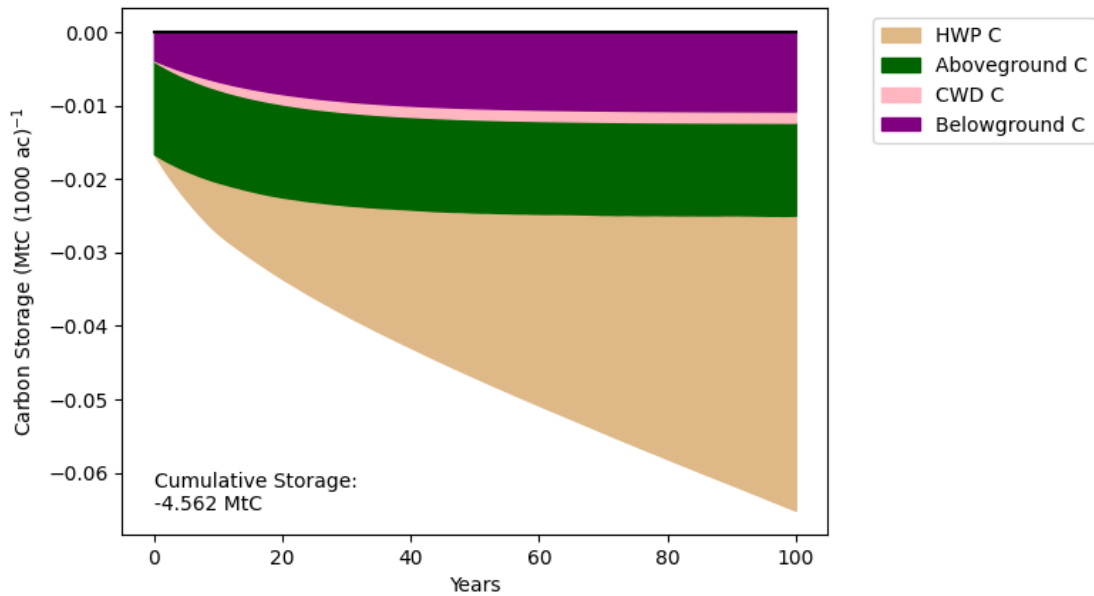


Figure 3.2. Carbon storage by pool ($C_{st,y}$) for scenario 1 with rotation length of 25.

Aboveground carbon storage was constant for all years in the time horizon within each regime because all carbon is either transferred to another carbon storage 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 acres (*e.g.*, Figure 3.2). 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 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.

3.3.2 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 both at planting and 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 3.3).

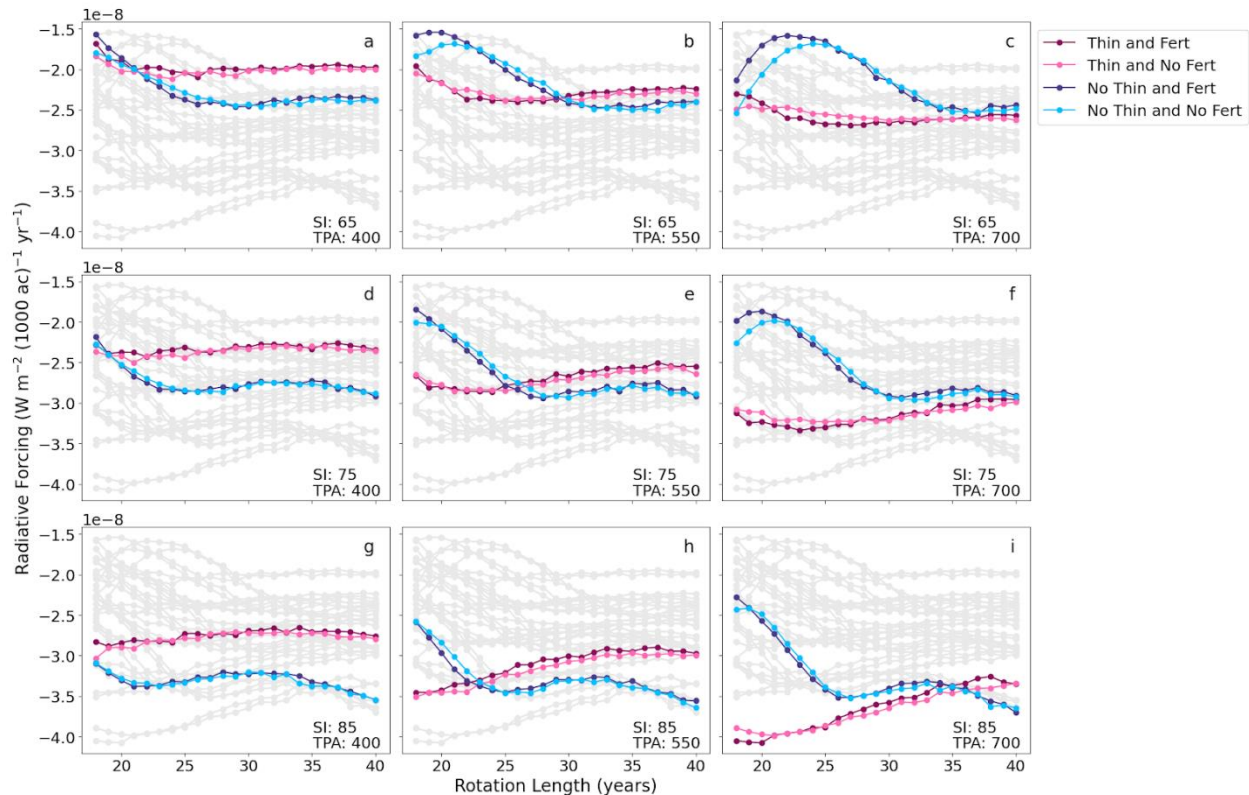


Figure 3.3. Average annual net radiative forcing ($netRF_{avg}$) for scenarios with varying site index (SI) and planting density (TPA).

For nearly all regimes, higher site index led to more climate benefits (*i.e.*, lower $netRF_{avg}$). Planting density had variable effects on $netRF_{avg}$. When a thinning was conducted, regimes with higher planting densities performed better for all rotation lengths. However, when no thinning was

conducted, regimes with lower planting densities performed better if rotations were short, and higher planting densities performed better if rotations were long. Thinning generally showed climate-positive effects when planting density was high (700 TPA) and climate-negative effects when planting density was low (400 TPA). 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 (SI 65, TPA 700, 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 3.3c).

Table 3.3. 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 (TPA) | Thinning | Fertilization | Harvest age (years) |
|-------------------|------------------|------------------------|----------|---------------|---------------------|
| Low (65) | Optimal | Moderate to high | Thin | Optional | ≥ 23 |
| | Alternative | Low | No thin | Optional | ≥ 26 |
| Medium (75) | Optimal | High | Thin | Optional | 19 - 30 |
| | Alternative | Low | No thin | Optional | ≥ 25 |
| High (85) | Optimal | High | Thin | Optional | 18 - 25 |
| | Alternative | Low to moderate | No thin | Optional | ≥ 23 |

SI = site index in ft for base age 25; TPA = trees per acre; low, moderate, and high planting densities are 400, 550, and 700 TPA, respectively.

The best-performing regime was scenario 9 (SI 85, TPA 700, thinned, with fertilization) on a 20-year rotation. The worst-performing regime was scenario 20 (SI 65, TPA 550, 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. 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 (154). 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.

3.3.3 Effect of Fossil Fuels

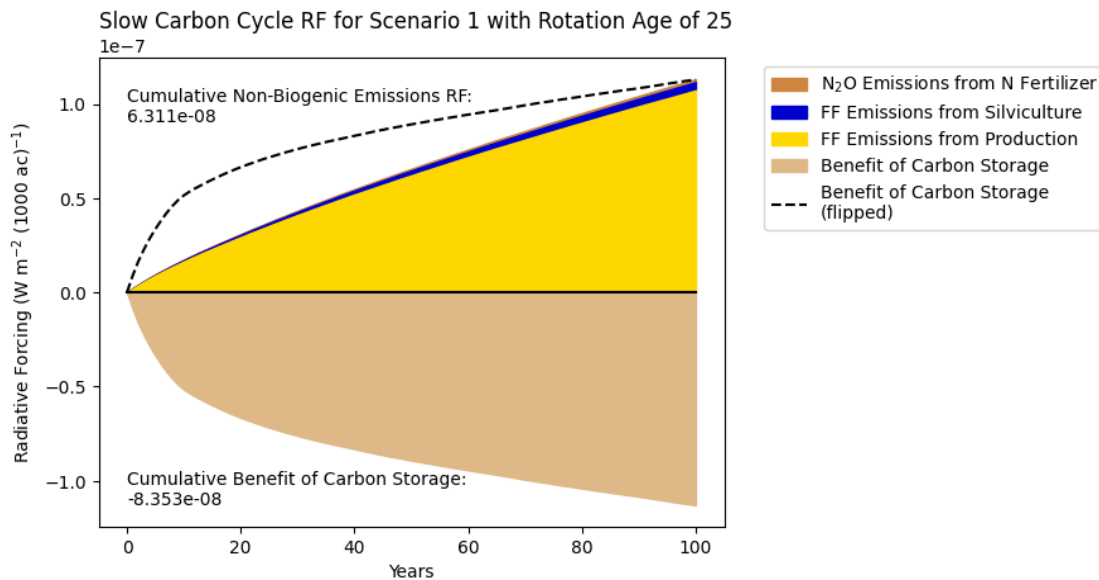


Figure 3.4. Radiative forcing from non-biogenic sources ($RF_{s,y}$) and climate benefit from carbon storage ($StorBen_y$) for scenario 1 with rotation length of 25.

For all regimes, the climate benefits from temporary and permanent carbon storage, $StorBen_y$, continued to increase for all years within the time horizon. As carbon in CWD, roots, and shorter-lived products 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 storage increased was

high (e.g., Figure 3.4). 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 storage 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 storage for all regimes within a few decades if the study time horizon were extended.

3.3.4 Effect of the Metric of Interest

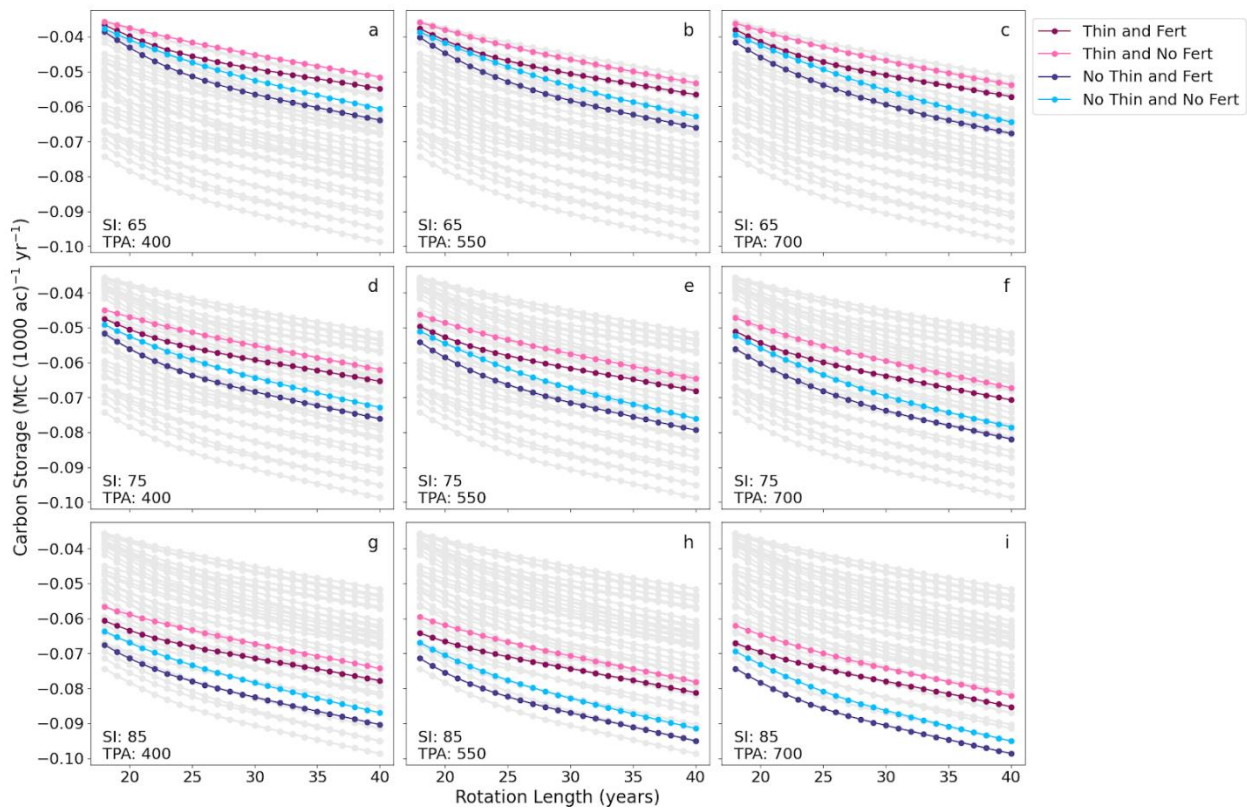


Figure 3.5. Average annual carbon storage over 100 years in *in situ* and *ex situ* pools (C_{avg}) for scenarios with varying site index (SI) and planting density (TPA).

When the metric used to measure climate benefits is average carbon storage (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 3.5).

3.4 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 storage (*i.e.*, C_{avg}) for loblolly pine in the southern US. 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 for all stands, lowered or had little effect on climate benefits for many scenarios.

Carbon storage failed to identify management strategies with the most climate benefits in many cases, since many regimes that produced comparatively high carbon storage also produced comparatively low cooling effects, and vice versa. When carbon storage was used to indicate climate effect, the results showed increased climate benefits from higher site quality, higher density throughout the rotation (*i.e.*, higher planting density and no thinning), fertilization, and longer rotations for all scenarios. Longer rotations are often used as a strategy to increase forest carbon storage (155). This strategy is potentially problematic for two reasons. First, although we found that for individual scenarios, longer rotations increased carbon storage, many regimes with short rotations had higher carbon storage 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 stored more carbon than the thinned fertilized scenario (S8) with a 30-year rotation. Puls et al. (130) similarly found that a 20-year rotation may store more carbon 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 effects of management on net radiative forcing varied considerably for different scenarios, highlighting the need to base management strategies on stand-specific conditions rather than applying generic strategies, such as extended rotations, to all stands. 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 (*e.g.*, 10,130). 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. (156,157), 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 (*e.g.*, 128,158). This discrepancy may be due in part to an underestimated growth response to fertilization in the FASTLOB model, compared to recent estimates of growth response by Albaugh et al. (159). However, differences in methodology, such as the emission sources included and the metric used to represent climate benefits, likely play an important role.

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 coarse woody debris prior to harvest.

Finally, some landowners may face challenges in securing loggers who are willing to conduct thinnings, and planting low density stands can eliminate the risk of having overstocked stands if thinning becomes unfeasible (160).

The results were also somewhat sensitive to the chosen temporal boundary, despite substantial efforts in the methodology design 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 was 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 placed in long-term and permanent storage in longer-lived products and landfills and (2) the extent of fossil fuel use. These factors essentially removed (carbon storage) and introduced (fossil fuels) carbon to the fast carbon cycle within the timescale of the study. Puls et al. (130) similarly found factors related to carbon storage in landfills, 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 storage, $StorBen_y$, 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 storage. Schulte et al. (161) 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 storage 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 (129,162,163), and these gains will likely continue in the future. Changing climatic factors such as CO₂ concentrations and precipitation will likely also affect future productivity (164). Further analysis is needed to understand how these changes affect the radiative forcing associated with loblolly plantations as we maintained static productivity over time. 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.

3.5 Conclusion

By modeling radiative forcing of forest management regimes applied to a 1000-acre landscape of loblolly pine plantations in the southern US, 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 thinning for high density stands but not for low density stands. 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 storage. 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 storage accounts only for sequestration and continued storage in biomass and wood products but ignores effects of non-biogenic and non-CO₂ emissions. Net radiative forcing is a more appropriate metric to assess climate effects, and our results show that carbon storage does 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.

CONCLUSION

For this project, we developed and parameterized a model that projects *ex situ* carbon flows, including biogenic and fossil fuel storage and emissions, from southern pine plantations in the southern US. Using this model, we assessed the effects of forest management on total carbon storage and radiative forcing associated with loblolly pine plantations. Results of our first study suggested that shorter rotations may lead to higher carbon storage in some cases when site quality is high. Although these results were not indicative of direct warming effects, they indicated possible climate benefits from adjusting forest management strategies based on site-specific conditions. In our second study, using the dynamic-LCA methodology proposed by Levasseur et al. (26) to calculate net radiative forcing, we found increased climate benefits from higher site quality, and developed management recommendations for each site quality class. In general, we found the most climate benefits were achieved within each site class when stands were planted at high densities (*e.g.*, 700 trees per acre) and thinned. Alternatively, climate benefits were also achieved when stands were planted at low densities (*e.g.*, 400 trees per acre) and not thinned. The optimal rotation length varied considerably depending on site quality and other management conditions. Our findings point to the complexity of the relationship between management and climate effects and the need for detailed accounting methods when designing forest mitigation strategies. Both studies further point to the importance of carbon storage in landfills and the consumption of fossil fuels, as these two factors drove the introduction and removal of carbon from the fast carbon cycle.

This research provides a comprehensive view of forest carbon dynamics by linking forest management strategies with wood product production to study their combined climate effects. Wood products from sustainably managed forests are a low-emission and renewable material and

should therefore be included in climate change mitigation strategies. By examining the carbon dynamics of both forest and wood product GHG fluxes, we are able to identify forest management strategies that not only represent the lowest emissions from the studied systems, but also facilitate the sustainable production of wood products. Our approach enables the consideration of complex trade-offs between sequestration and emissions from forests and wood products, as well as effects of temporary carbon storage. The modeling tools we developed can further be used for integrated assessment approaches that analyze economic and land-use trade-offs of mitigation policies to develop practical climate solutions.

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APPENDICES

APPENDIX

Text 1. Secondary Product Use Category Descriptions

New residential construction- All wood products used in the construction of housing built in year 0 for single family housing, multi-family housing, and manufactured housing. Does not include furniture but does include permanent furnishings. Sub-categories include floors, walls, roofs, foundations, decks, exterior doors, interior doors, garage doors, windows, moulding, shelving, cabinets, and countertops. Does not include outdoor fence posts. (70,165,166)

Residential upkeep - All wood products used in maintenance, repair, additions, alterations, and replacements done on single family housing, multi-family housing, and manufactured housing. (70)

New building construction - All wood products used in the construction of lodging, office, commercial, healthcare, educational, religious, public safety, amusement and recreation, and manufactured buildings built in year 0. (70)

Other new structures - All wood products used in the construction of transportation, communication, dams, power, highway and street, sewage and waste disposal, water supply, and conservation and development projects built in year 0. Does not include utility poles or marine pilings. (70)

Other construction (non-residential upkeep, etc.) - All wood products used in maintenance, repair, additions, alterations, and replacements done to non-residential buildings and structures, and any other wood products used in construction and not included elsewhere (70).

Pallets - Includes wooden shipping pallets.

Other shipping - Includes wood boxes, crates, hampers, baskets, dunnage, blocking, bracing, and all other wood products used in shipping and handling, excluding pallets. (70)

Poles - All wooden utility poles.

Posts and pilings - Marine pilings and fence posts. Consumption data for this category, as separate from “poles,” “other new structures,” or “miscellaneous,” were not available. This category was created separately from “poles” to account for the shorter life span of marine pilings vs. utility poles. It was created separately from “other new structures” to account for recycling of treated wood from utility poles and the shorter lifespans of these downcycled products.

Bedding - Wood chips, shavings, or sawdust used by animals, including livestock, poultry, horses, small pets, etc.

Landscaping - Includes bark and chip mulch and any other wood product or byproduct used in landscaping.

Corrugated Boxes - Includes linerboard kraft, which typically makes up the outer layer of corrugated boxes, and corrugating medium, which typically is used for the fluting or middle layer (167).

Sanitary Products - Includes commercial and retail bathroom tissue, facial tissue, and other tissue. Excludes food and kitchen related tissues such as napkins and paper towels. Also includes products manufactured with wood fluff, such as diapers, incontinence pads, and menstrual products (167).

Packaging Cartonboard - Includes virgin cartonboard products used for packaging a variety of grocery store and other retail items. This category is intended for cartonboard that is kept relatively clean and may therefore be recycled. It includes cartonboard products such as soda, beer, and other beverage carriers; boxes containing dry and frozen food, auto parts, toys, etc.; cigarette cartons; milk and juice cartons; etc. (167).

Disposable Food Related Products - Includes a variety of paper products used to package, carry, eat, or clean food and other contaminating products. This category is intended for items that are not typically recycled. It includes products such as paper bags; pet food and cement bags; fast food wrappers; microwavable popcorn bags; butter and meat wrappers; paper napkins and towels; paper plates, cups, and bowls; etc. (167).

Miscellaneous Paper Products - Includes cigarette filters, cellophane, rayon, newsprint, bristols, and any other pulp and paper products not included in previous categories (167).

Furniture - Includes household, commercial, and institutional furniture. (70)

Other manufacturing - Includes all manufactured items that are not furniture, such as musical instruments, sports equipment, toys, brooms and mops, caskets, etc. (70)

Miscellaneous - Wood products that do not fit into other categories, including craft and hobby projects, advertising structures, excelsior, mining supports, wood flour, non-structural wood used in non-residential construction, etc. (70)

Tables A1-25. Parameters Used in LobWISE

Table A1. General end use category by primary product

| Primary Product | End Use Category | Portion | Source |
|----------------------------------|----------------------------------|----------------|----------------------------|
| Lumber | New Residential | 0.317 | (70) |
| | Residential Upkeep | 0.305 | (70) |
| | New Non-residential | 0.067 | (70) |
| | Shipping | 0.169 | (70) |
| | Manufacturing | 0.08 | (70) |
| | Other | 0.054 | (70) |
| Softwood Plywood | New Residential | 0.485 | (70) |
| | Residential Upkeep | 0.232 | (70) |
| | New Non-residential | 0.058 | (70) |
| | Shipping | 0.059 | (70) |
| | Manufacturing | 0.09 | (70) |
| | Other | 0.077 | (70) |
| OSB | New Residential | 0.485 | (70) |
| | Residential Upkeep | 0.232 | (70) |
| | New Non-residential | 0.058 | (70) |
| | Shipping | 0.059 | (70) |
| | Manufacturing | 0.09 | (70) |
| | Other | 0.077 | (70) |
| Non-Structural Panels | New Residential | 0.014 | (70) |
| | Residential Upkeep | 0.216 | (70) |
| | New Non-residential | 0.058 | (70) |
| | Shipping | 0.03 | (70) |
| | Manufacturing | 0.37 | (70) |
| | Other | 0.314 | (70) |
| Engineered Wood | New Residential | 0.8 | Professional judgment |
| | Residential Upkeep | 0.05 | Professional judgment |
| | New Non-residential | 0.15 | Professional judgment |
| | Shipping | 0 | Professional judgment |
| | Manufacturing | 0 | Professional judgment |
| | Other | 0 | Professional judgment |
| Poles and Pilings | Poles | 0.35 | (71) professional judgment |
| | Posts and Pilings | 0.65 | (71) professional judgment |
| | New Residential | 0 | Professional judgment |
| | Residential Upkeep | 0 | Professional judgment |
| | New Non-residential | 0 | Professional judgment |
| | Shipping | 0 | Professional judgment |
| | Manufacturing | 0 | Professional judgment |
| | Other | 0 | Professional judgment |
| | | | |
| Paper and Paper Products | | | |
| | From Roundwood | | |
| | Corrugated Boxes | 0.556 | (167) |
| | Sanitary Products | 0.227 | (167) |
| | Packaging Cartonboard | 0.120 | (167) |
| | Disposable Food Related Products | 0.061 | (167) |
| | Miscellaneous Paper Products | 0.036 | (167) |
| | From Coarse Residue | | |
| | Corrugated Boxes | 0.608 | (167) |
| | Sanitary Products | 0.196 | (167) |
| Packaging Cartonboard | 0.099 | (167) | |
| Disposable Food Related Products | 0.068 | (167) | |
| Miscellaneous Paper Products | 0.029 | (167) | |

Table A1 (continued).

| | | | |
|-------------------|----------------------------------|-------|-------|
| From Fine Residue | Corrugated Boxes | 0 | (167) |
| | Sanitary Products | 0.498 | (167) |
| | Packaging Cartonboard | 0 | (167) |
| | Disposable Food Related Products | 0.502 | (167) |
| | Miscellaneous Paper Products | 0 | (167) |

Table A2. Specific end use category by primary product and general end use

| Primary Product | General End Use | Specific End Use | Portion | Source |
|------------------|---------------------|---------------------|---------|-----------------------|
| Lumber | New Residential | Manufactured | 0.042 | (70) |
| | | Multi-family homes | 0.125 | (70) |
| | | Single family homes | 0.833 | (70) |
| | Residential Upkeep | Manufactured | 0.042 | * |
| | | Multi-family homes | 0.125 | * |
| | | Single family homes | 0.833 | * |
| | New Non-residential | Buildings | 0.627 | (70) |
| | | Other | 0.373 | (70) |
| | Shipping | Pallets | 0.92 | (70) |
| | | Other | 0.08 | (70) |
| | Manufacturing | Furniture | 0.284 | (70) |
| | | Other | 0.716 | (70) |
| Softwood Plywood | New Residential | Manufactured | 0.037 | (70) |
| | | Multi-family homes | 0.11 | (70) |
| | | Single family homes | 0.853 | (70) |
| | Residential Upkeep | Manufactured | 0.037 | * |
| | | Multi-family homes | 0.11 | * |
| | | Single family homes | 0.853 | * |
| | New Non-residential | Buildings | 0.882 | (70) |
| | | Other | 0.118 | (70) |
| | Shipping | Pallets | 0 | Professional judgment |
| | | Other | 1 | Professional judgment |
| | Manufacturing | Furniture | 0.225 | (70) |
| | | Other | 0.775 | (70) |
| OSB | New Residential | Manufactured | 0.037 | (70) |
| | | Multi-family homes | 0.11 | (70) |
| | | Single family homes | 0.853 | (70) |
| | Residential Upkeep | Manufactured | 0.037 | * |
| | | Multi-family homes | 0.11 | * |
| | | Single family homes | 0.853 | * |
| | New Non-residential | Buildings | 0.882 | (70) |
| | | Other | 0.118 | (70) |
| | Shipping | Pallets | 0 | Professional judgment |
| | | Other | 1 | Professional judgment |
| | Manufacturing | Furniture | 0.225 | (70) |
| | | Other | 0.775 | (70) |

Table A2 (continued).

| | | | | |
|-----------------------|---------------------|---------------------|-------|-----------------------|
| Non-Structural Panels | New Residential | Manufactured | 0.823 | (70) |
| | | Multi-family homes | 0.002 | (70) |
| | | Single family homes | 0.175 | (70) |
| | Residential Upkeep | Manufactured | 0.823 | * |
| | | Multi-family homes | 0.002 | * |
| | | Single family homes | 0.175 | * |
| | New Non-residential | Buildings | 0.006 | (70) |
| | | Other | 0.994 | (70) |
| | Shipping | Pallets | 0 | Professional judgment |
| | | Other | 1 | Professional judgment |
| | Manufacturing | Furniture | 0.438 | (70) |
| | | Other | 0.562 | (70) |
| Engineered Wood | New Residential | Manufactured | 0.05 | Professional judgment |
| | | Multi-family homes | 0.202 | (166) |
| | | Single family homes | 0.748 | (166) |
| | Residential Upkeep | Manufactured | 0.05 | * |
| | | Multi-family homes | 0.202 | * |
| | | Single family homes | 0.748 | * |
| | New Non-residential | Buildings | 1 | Professional judgment |
| | | Other | 0 | Professional judgment |
| | Shipping | Pallets | 0 | Professional judgment |
| | | Other | 1 | Professional judgment |
| | Manufacturing | Furniture | 0.5 | Professional judgment |
| | | Other | 0.5 | Professional judgment |
| Poles and Pilings | New Residential | Manufactured | 0 | Professional judgment |
| | | Multi-family homes | 0 | Professional judgment |
| | | Single family homes | 1 | Professional judgment |
| | Residential Upkeep | Manufactured | 0 | * |
| | | Multi-family homes | 0 | * |
| | | Single family homes | 1 | * |
| | New Non-residential | Buildings | 1 | Professional judgment |
| | | Other | 0 | Professional judgment |
| | Shipping | Pallets | 0 | --- |
| | | Other | 1 | --- |
| | Manufacturing | Furniture | 1 | Professional judgment |
| | | Other | 0 | Professional judgment |

*Upkeep portions are assumed to be the same as new construction.

Table A3. Lifespans of single family housing parts

| Housing Part | Material | Modal Estimate (<i>mode</i>) | Scale Factor (λ) | Shape Factor (<i>k</i>) | Source |
|---|---------------------|-----------------------------------|-------------------------------|------------------------------|--------------------------------|
| Single Family Home (whole house) | | 125 | 150 | 2.63 | (72) |
| Floors | Lumber | 112 | 135 | 2.63 | (72,168) professional judgment |
| Walls | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Roofs | | 125 | 150 | 2.63 | (72,168) |
| Foundations | | 125 | 150 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Interior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Shelving | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | | 50 | 60 | 2.63 | (72,168) |
| Countertops | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Floors | | Engineered Wood | 112 | 135 | 2.63 |
| Walls | 112 | | 135 | 2.63 | (72,168) professional judgment |
| Roofs | 125 | | 150 | 2.63 | (72,168) |
| Foundations | 125 | | 150 | 2.63 | (72,168) |
| Decks | 13 | | 16 | 2.63 | (71) |
| Exterior doors | 112 | | 135 | 2.63 | (72,168) professional judgment |
| Interior doors | 112 | | 135 | 2.63 | (72,168) professional judgment |
| Garage doors | 25 | | 30 | 2.63 | (169) |
| Windows | 30 | | 36 | 2.63 | (72,168) |
| Moulding | 112 | | 135 | 2.63 | (72,168) professional judgment |
| Shelving | 100 | | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | 50 | | 60 | 2.63 | (72,168) |
| Countertops | 100 | | 120 | 2.63 | (72,168) professional judgment |
| Floors | Softwood Plywood | | 112 | 135 | 2.63 |
| Walls | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Roofs | | 125 | 150 | 2.63 | (72,168) |
| Foundations | | 125 | 150 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Interior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Shelving | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | | 40 | 48 | 2.63 | (72,168) professional judgment |
| Countertops | | 100 | 120 | 2.63 | (72,168) professional judgment |

Table A3 (continued).

| | | | | | |
|----------------|-------------------|-----|-----|------|--------------------------------|
| Floors | OSB | 112 | 135 | 2.63 | (72,168) professional judgment |
| Walls | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Roofs | | 125 | 150 | 2.63 | (72,168) |
| Foundations | | 125 | 150 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Interior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Shelving | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | | 40 | 48 | 2.63 | (72,168) professional judgment |
| Countertops | | 100 | 120 | 2.63 | (72,168) professional judgment |
| | Non-Structural | | | | |
| Floors | Panels | 112 | 135 | 2.63 | (72,168) professional judgment |
| Walls | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Roofs | | 125 | 150 | 2.63 | (72,168) |
| Foundations | | 125 | 150 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Interior doors | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 112 | 135 | 2.63 | (72,168) professional judgment |
| Shelving | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | | 40 | 48 | 2.63 | (72,168) professional judgment |
| Countertops | | 100 | 120 | 2.63 | (72,168) professional judgment |
| | Poles and Pilings | | | | |
| Floors | | 125 | 150 | 2.63 | (72,168) professional judgment |
| Walls | | 125 | 150 | 2.63 | (72,168) |
| Roofs | | 125 | 150 | 2.63 | (72,168) |
| Foundations | | 125 | 150 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 125 | 150 | 2.63 | (72,168) |
| Interior doors | | 125 | 150 | 2.63 | (72,168) |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 125 | 150 | 2.63 | (72,168) |
| Shelving | | 100 | 120 | 2.63 | (72,168) professional judgment |
| Cabinets | | 50 | 60 | 2.63 | (72,168) |
| Countertops | | 100 | 120 | 2.63 | (72,168) professional judgment |

Table A4. Lifespans of multi-family housing parts

| Housing Part | Material | Modal Estimate (<i>mode</i>) | Scale Factor (λ) | Shape Factor (k) | Source |
|---------------------------------------|------------------|-----------------------------------|-------------------------------|-------------------------|--------------------------------|
| Multi-Family Home (whole unit) | | 110 | 132 | 2.63 | (72) professional judgment |
| Floors | Lumber | 99 | 119 | 2.63 | (72,168) professional judgment |
| Walls | | 99 | 119 | 2.63 | (72,168) professional judgment |
| Roofs | | 110 | 132 | 2.63 | (72,168) |
| Foundations | | 110 | 132 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Interior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Shelving | | 77 | 92 | 2.63 | (72,168) professional judgment |
| Cabinets | | 40 | 48 | 2.63 | (72,168) professional judgment |
| Countertops | | 77 | 92 | 2.63 | (72,168) professional judgment |
| Floors | | Engineered Wood | 99 | 119 | 2.63 |
| Walls | 99 | | 119 | 2.63 | (72,168) professional judgment |
| Roofs | 110 | | 132 | 2.63 | (72,168) |
| Foundations | 110 | | 132 | 2.63 | (72,168) |
| Decks | 13 | | 16 | 2.63 | (71) |
| Exterior doors | 88 | | 106 | 2.63 | (72,168) professional judgment |
| Interior doors | 88 | | 106 | 2.63 | (72,168) professional judgment |
| Garage doors | 25 | | 30 | 2.63 | (169) |
| Windows | 30 | | 36 | 2.63 | (72,168) |
| Moulding | 88 | | 106 | 2.63 | (72,168) professional judgment |
| Shelving | 77 | | 92 | 2.63 | (72,168) professional judgment |
| Cabinets | 40 | | 48 | 2.63 | (72,168) professional judgment |
| Countertops | 77 | | 92 | 2.63 | (72,168) professional judgment |
| Floors | Softwood Plywood | | 99 | 119 | 2.63 |
| Walls | | 99 | 119 | 2.63 | (72,168) professional judgment |
| Roofs | | 110 | 132 | 2.63 | (72,168) |
| Foundations | | 110 | 132 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Interior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Shelving | | 77 | 92 | 2.63 | (72,168) professional judgment |
| Cabinets | | 30 | 36 | 2.63 | (72,168) professional judgment |
| Countertops | | 77 | 92 | 2.63 | (72,168) professional judgment |

Table A4 (continued).

| | | | | | |
|----------------|-------------------|-----|-----|------|--------------------------------|
| Floors | OSB | 99 | 119 | 2.63 | (72,168) professional judgment |
| Walls | | 99 | 119 | 2.63 | (72,168) professional judgment |
| Roofs | | 110 | 132 | 2.63 | (72,168) |
| Foundations | | 110 | 132 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Interior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Shelving | | 77 | 92 | 2.63 | (72,168) professional judgment |
| Cabinets | | 30 | 36 | 2.63 | (72,168) professional judgment |
| Countertops | | 77 | 92 | 2.63 | (72,168) professional judgment |
| | Non-Structural | | | | |
| Floors | Panels | 99 | 119 | 2.63 | (72,168) professional judgment |
| Walls | | 99 | 119 | 2.63 | (72,168) professional judgment |
| Roofs | | 110 | 132 | 2.63 | (72,168) |
| Foundations | | 110 | 132 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Interior doors | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 88 | 106 | 2.63 | (72,168) professional judgment |
| Shelving | | 77 | 92 | 2.63 | (72,168) professional judgment |
| Cabinets | | 30 | 36 | 2.63 | (72,168) professional judgment |
| Countertops | | 77 | 92 | 2.63 | (72,168) professional judgment |
| | Poles and Pilings | | | | |
| Floors | | 110 | 132 | 2.63 | (72,168) |
| Walls | | 110 | 132 | 2.63 | (72,168) |
| Roofs | | 110 | 132 | 2.63 | (72,168) |
| Foundations | | 110 | 132 | 2.63 | (72,168) |
| Decks | | 13 | 16 | 2.63 | (71) |
| Exterior doors | | 110 | 132 | 2.63 | (72,168) |
| Interior doors | | 110 | 132 | 2.63 | (72,168) |
| Garage doors | | 25 | 30 | 2.63 | (169) |
| Windows | | 30 | 36 | 2.63 | (72,168) |
| Moulding | | 110 | 132 | 2.63 | (72,168) |
| Shelving | | 110 | 132 | 2.63 | (72,168) |
| Cabinets | | 40 | 48 | 2.63 | (72,168) professional judgment |
| Countertops | | 110 | 132 | 2.63 | (72,168) |

Table A5. Lifespans of other products

| Housing Part | Modal Estimate (mode) | Scale Factor (λ) | Shape Factor (k) | Source |
|--------------------------------------|----------------------------------|--|--|------------------------------------|
| Manufactured home | 70 | 84 | 2.63 | (72) professional judgment |
| Single family home upkeep | 37 | 45 | 2.63 | (42,72) |
| Multi-family home upkeep | 33 | 40 | 2.63 | (42,72) |
| Manufactured upkeep | 21 | 25 | 2.63 | (42,72) |
| Building | 70 | 84 | 2.63 | (72,73,170,171) |
| Other new structure | 60 | 72 | 2.63 | (72,172–174) |
| Other (non-residential upkeep, etc.) | 21 | 25 | 2.63 | (42,72,73,170,171) |
| Pallets | 1 | 1 | 2.63 | (72,175) |
| Other shipping | 2 | 2 | 2.63 | Professional judgment |
| Poles | 60 | 72 | 2.63 | (72,176) |
| Posts/pilings | 30 | 36 | 2.63 | (72,169,177) professional judgment |
| Bedding | 1 | 1 | 2.63 | Professional judgment |
| Landscaping | 2 | 2 | 2.63 | (72,178) |
| Corrugated boxes | 1 | 1 | 2.63 | (103) professional judgment |
| Sanitary products | 1 | 1 | 2.63 | (103) professional judgment |
| Packaging cartonboard | 1 | 1 | 2.63 | (103) professional judgment |
| Disposable food related products | 1 | 1 | 2.63 | (103,179) professional judgment |
| Miscellaneous paper products | 1 | 1 | 2.63 | (103) professional judgment |
| Furniture | 13 | 16 | 2.63 | (72,179) |
| Other manufacturing | 7 | 8 | 2.63 | (72,180–183) professional judgment |
| Miscellaneous | 4 | 5 | 2.63 | Professional judgment |

Table A6. Portion of transitioned product that is landfilled

| Secondary Product | MSW Landfill | C&D Landfill | Source |
|--------------------------------------|---------------------|-------------------------|----------------------------|
| Single family homes | 0 | 0.722 | (103) |
| Multi-family homes | 0 | 0.722 | (103) |
| Manufactured home | 0 | 0.722 | (103) |
| Single family home upkeep | 0 | 0.722 | (103) |
| Multi-family home upkeep | 0 | 0.722 | (103) |
| Manufactured upkeep | 0 | 0.722 | (103) |
| Building | 0 | 0.722 | (103) |
| Other new structure | 0 | 0.722 | (103) |
| Other (non-residential upkeep, etc.) | 0 | 0.722 | (103) |
| Pallets | 0.007 | 0.003 | (184,185) |
| Other shipping | 0.632 | 0 | (186) |
| Poles | 0 | 0.32 | (176) |
| Posts/pilings | 0 | 0.7 | (177) |
| Bedding | 0.5 | 0 | Professional judgment |
| Landscaping | 0 | 0 | Professional judgment |
| Corrugated boxes | 0.028 | 0 | (75) |
| Sanitary products | 0.656 | 0 | (75,167,187) |
| Packaging cartonboard | 0.640 | 0 | (75) |
| Disposable food related products | 0.819 | 0 | (75) |
| Miscellaneous paper products | 0.578 | 0 | (75) |
| Furniture | 0.801 | 0 | (75) |
| Other manufacturing | 0.801 | 0 | (75) professional judgment |
| Miscellaneous | 0.801 | 0 | (75) professional judgment |

Table A7. Portion of transitioned product that is downcycled as landscaping.

| Secondary Product | Portion | Source |
|--------------------------------------|---------|---------------------------------|
| Single family homes | 0.061 | (103) |
| Multi-family homes | 0.061 | (103) |
| Manufactured home | 0.061 | (103) |
| Single family home upkeep | 0.061 | (103) |
| Multi-family home upkeep | 0.061 | (103) |
| Manufactured upkeep | 0.061 | (103) |
| Building | 0.061 | (103) |
| Other new structure | 0.061 | (103) |
| Other (non-residential upkeep, etc.) | 0.061 | (103) |
| Pallets | 0.109 | (185) |
| Other shipping | 0.138 | (185,186) professional judgment |
| Poles | 0.061 | * |
| Posts/pilings | -- | --- |
| Bedding | -- | --- |
| Landscaping | -- | --- |
| Corrugated boxes | 0 | Professional judgment |
| Sanitary products | 0 | Professional judgment |
| Packaging cartonboard | 0 | Professional judgment |
| Disposable food related products | 0 | Professional judgment |
| Miscellaneous paper products | 0 | Professional judgment |
| Furniture | -- | Professional judgment |
| Other manufacturing | -- | Professional judgment |
| Miscellaneous | 0 | Professional judgment |

*The rate of pole downcycling is assumed to be the same as the rate for C&D waste.

Table A8. Portion of transitioned product that is downcycled as bedding.

| Secondary Product | Portion | Source |
|--------------------------------------|---------|--------|
| Single family homes | 0 | --- |
| Multi-family homes | 0 | --- |
| Manufactured home | 0 | --- |
| Single family home upkeep | 0 | --- |
| Multi-family home upkeep | 0 | --- |
| Manufactured upkeep | 0 | --- |
| Building | 0 | --- |
| Other new structure | 0 | --- |
| Other (non-residential upkeep, etc.) | 0 | --- |
| Pallets | 0.012 | (185) |
| Other shipping | 0 | --- |
| Poles | 0 | --- |
| Posts/pilings | -- | --- |
| Bedding | -- | --- |
| Landscaping | -- | --- |
| Corrugated boxes | 0 | --- |
| Sanitary products | 0 | --- |
| Packaging cartonboard | 0 | --- |
| Disposable food related products | 0 | --- |
| Miscellaneous paper products | 0 | --- |
| Furniture | -- | --- |
| Other manufacturing | -- | --- |
| Miscellaneous | 0 | --- |

Table A9. Portion of transitioned product that is downcycled as posts and pilings.

| Secondary Product | Portion | Source |
|--------------------------------------|----------------|---------------|
| Single family homes | 0 | --- |
| Multi-family homes | 0 | --- |
| Manufactured home | 0 | --- |
| Single family home upkeep | 0 | --- |
| Multi-family home upkeep | 0 | --- |
| Manufactured upkeep | 0 | --- |
| Building | 0 | --- |
| Other new structure | 0 | --- |
| Other (non-residential upkeep, etc.) | 0 | --- |
| Pallets | 0 | --- |
| Other shipping | 0 | --- |
| Poles | 0.409 | (103,177) |
| Posts/pilings | -- | --- |
| Bedding | -- | --- |
| Landscaping | -- | --- |
| Corrugated boxes | 0 | --- |
| Sanitary products | 0 | --- |
| Packaging cartonboard | 0 | --- |
| Disposable food related products | 0 | --- |
| Miscellaneous paper products | 0 | --- |
| Furniture | -- | --- |
| Other manufacturing | -- | --- |
| Miscellaneous | 0 | --- |

Table A10. Portion of transitioned product that is downcycled as structural panels.

| Secondary Product | Portion | Source |
|--------------------------------------|----------------|-----------------------|
| Single family homes | 0 | Professional judgment |
| Multi-family homes | 0 | Professional judgment |
| Manufactured home | 0 | Professional judgment |
| Single family home upkeep | 0 | Professional judgment |
| Multi-family home upkeep | 0 | Professional judgment |
| Manufactured upkeep | 0 | Professional judgment |
| Building | 0 | Professional judgment |
| Other new structure | 0 | Professional judgment |
| Other (non-residential upkeep, etc.) | 0 | Professional judgment |
| Pallets | 0 | --- |
| Other shipping | 0 | --- |
| Poles | 0 | --- |
| Posts/pilings | -- | --- |
| Bedding | -- | --- |
| Landscaping | -- | --- |
| Corrugated boxes | 0 | --- |
| Sanitary products | 0 | --- |
| Packaging cartonboard | 0 | --- |
| Disposable food related products | 0 | --- |
| Miscellaneous paper products | 0 | --- |
| Furniture | -- | --- |
| Other manufacturing | -- | --- |
| Miscellaneous | 0 | --- |

Table A11. Portion of transitioned product that is downcycled as non-structural panels.

| Secondary Product | Portion | Source |
|--------------------------------------|---------|-----------------------------|
| Single family homes | 0.029 | (103) professional judgment |
| Multi-family homes | 0.029 | (103) professional judgment |
| Manufactured home | 0.029 | (103) professional judgment |
| Single family home upkeep | 0.029 | (103) professional judgment |
| Multi-family home upkeep | 0.029 | (103) professional judgment |
| Manufactured upkeep | 0.029 | (103) professional judgment |
| Building | 0.029 | (103) professional judgment |
| Other new structure | 0.029 | (103) professional judgment |
| Other (non-residential upkeep, etc.) | 0.029 | (103) professional judgment |
| Pallets | 0 | --- |
| Other shipping | 0 | --- |
| Poles | 0 | --- |
| Posts/pilings | -- | --- |
| Bedding | -- | --- |
| Landscaping | -- | --- |
| Corrugated boxes | 0 | --- |
| Sanitary products | 0 | --- |
| Packaging cartonboard | 0 | --- |
| Disposable food related products | 0 | --- |
| Miscellaneous paper products | 0 | --- |
| Furniture | -- | --- |
| Other manufacturing | -- | --- |
| Miscellaneous | 0 | --- |

Table A12. Fossil fuel emission factors.

| Primary Product | Procurement | Transportation | Production | Source |
|--------------------------|-------------|----------------|------------|-----------|
| Lumber | 0.0186 | 0.0168 | 0.0882 | (11) |
| Plywood | 0.0715 | 0.0096 | 0.1906 | (188) |
| OSB | 0.0687 | 0.0060 | 0.1309 | (113) |
| Non-structural panels | 0.2007 | 0.0057 | 0.2360 | (114,115) |
| Engineered wood | --- | --- | 0.3902* | (116–121) |
| Poles | 0.0186 | 0.0168 | 0.0882 | ** |
| Paper and paper products | 0.0533 | 0.0484 | 0.4162 | (111) |
| Pellets | --- | --- | 0.0867*** | (110) |

Emission factors are in tCO₂e emitted per tCO₂e stored in final product; all fossil fuel emissions are assumed to be in CO₂e in year 0; *emissions for engineered wood products included the procurement, transportation, and production emissions of the main primary product (*i.e.*, lumber, plywood, or OSB) plus the production emissions for engineered wood; **the emission factors for poles are assumed to be the same as the factors for sawtimber; ***a breakdown of emission factors for pellets by life stage was not available, but this factor includes procurement, transportation, and production emissions for pellets manufactured from roundwood; fossil fuel emissions for primary products manufactured from mill residue included the procurement and transportation emissions for the intended primary product and the production emissions for the actual primary product.

Table A13. Landfill decay parameters.

| Parameter | MSW Landfills | C&D Landfills | Source |
|--|---------------|---------------|--------|
| Fraction of paper carbon that will decay (DOC _f) | 0.262 | 0.262 | (15) |
| Fraction of wood carbon that will decay (DOC _f) | 0.029 | 0.029 | (14) |
| Half-life of decayable paper carbon (t _{1/2}) | 15 | 15 | (15) |
| Half-life of decayable wood carbon (t _{1/2}) | 30 | 30 | (15) |

Table A14. Landfill methane parameters.

| Parameter | MSW Landfills | C&D Landfills | Source |
|--|---------------|---------------|--------|
| F (portion of landfill gas that is CH ₄ by volume) | 0.5 | 0.5 | (74) |
| R (portion of generated CH ₄ that is recovered) | 0.6 | 0 | (43) |
| OX (portion of non-recovered CH ₄ that is oxidized) | 0.22 | 0.1 | (43) |
| Methane to CO _{2e} conversion factor | 30 | 30 | (111) |

Table A15. Waste deduction parameters.

| Parameter | Portion | Source |
|---|---------|------------|
| Portion of carbon transitioned from housing pool at time of construction | 0.056 | (57,70,71) |
| Portion of carbon transitioned from other pools at time of manufacture (excludes poles, landscaping, and bedding) | 0.08 | (56) |

Table A16. Portion of primary product carbon used to produce engineered wood.

| Primary Product | Portion | Source |
|------------------|---------|----------------------------|
| Lumber | 0.03 | (70) professional judgment |
| Softwood Plywood | 0.06 | (70) professional judgment |
| OSB | 0.1 | (70) professional judgment |

Engineered wood products include glued laminated timber (glulam), cross-laminated timber (CLT), nail-laminated timber (NLT), I-joists, laminated veneer lumber (LVL), parallel-strand lumber (PSL), laminated strand lumber (LSL), oriented strand lumber (OSL), OSB rim boards, and softwood plywood rim boards.

Table A17. Portion of carbon in logs of each size class that is used as each log type (*i.e.*, cull factors).

| Log Type | Poletimber sized logs (13-22 cm DBH) | Sawtimber sized logs (23+ cm DBH) | Source |
|----------------|--------------------------------------|-----------------------------------|--------|
| Pulp Logs | 0.827 | 0.162 | (69) |
| Saw Logs | 0.042 | 0.692 | (69) |
| Veneer Logs | 0.046 | 0.086 | (69) |
| Pole Logs | 0.009 | 0.009 | (69) |
| Composite Logs | 0.044 | 0.028 | (69) |
| Bioenergy Logs | 0.032 | 0.022 | (69) |

DBH = diameter at breast height.

Table A18. Portion of log carbon used in primary products and mill residue.

| Log Type | Primary Product or Residue Type | Portion | Source | |
|-----------------|--|----------------|---------------|---|
| Sawtimber logs | 23-32 cm DBH | Lumber | 0.35 | (11,68,108,189) professional judgment (69) |
| | | Bark | 0.09 | |
| | | Coarse residue | 0.31 | |
| | | Fine residue | 0.25 | |
| | 33-47 cm DBH | Lumber | 0.40 | (11,68,108,189) professional judgment (69) |
| | | Bark | 0.08 | |
| | | Coarse residue | 0.29 | |
| | | Fine residue | 0.23 | |
| | 48+ cm DBH | Lumber | 0.50 | (11,68,108,189) professional judgment (69) |
| | | Bark | 0.07 | |
| | | Coarse residue | 0.24 | |
| | | Fine residue | 0.19 | |
| Pulpwood logs | Pulp or paper | 0.89 | (69) | |
| | Bark | 0.11 | (69) | |
| Veneer logs | Plywood | 0.41 | (69) | |
| | Bark | 0.09 | (69) | |
| | Coarse residue | 0.3 | (69) | |
| | Fine residue | 0.23 | (69) | |
| Pole logs | Poles | 0.81 | (69) | |
| | Bark | 0.13 | (69) | |
| | Coarse residue | 0.06 | (69) | |
| Bioenergy logs | Bioenergy products | 0.9 | (69) | |
| | Bark | 0.1 | (69) | |
| Composite logs | OSB | 0.9 | (69) | |
| | Bark | 0.1 | (69) | |

Table A19. Mill residue use.

| Log Type | Residue Type | Use | Portion | Source |
|----------------|----------------|------------------|---------|--------|
| Sawtimber logs | Bark | Landscaping | 0.48 | (69) |
| | | Miscellaneous | 0.02 | (69) |
| | | Fiber product | 0.01 | (69) |
| | | Pellets | 0.02 | (69) |
| | | Otherwise burned | 0.47 | (69) |
| | Coarse residue | Landscaping | 0.01 | (69) |
| | | Miscellaneous | 0.095 | (69) |
| | | Fiber product | 0.79 | (69) |
| | | Animal bedding | 0.005 | (69) |
| | | Pellets | 0.02 | (69) |
| | Fine residue | Otherwise burned | 0.08 | (69) |
| | | Landscaping | 0.01 | (69) |
| | | Miscellaneous | 0.03 | (69) |
| | | Fiber product | 0.11 | (69) |
| | | Animal bedding | 0.08 | (69) |
| Pulpwood logs | Bark | Pellets | 0.19 | (69) |
| | | Otherwise burned | 0.58 | (69) |
| | | Landscaping | 0.03 | (69) |
| Veneer logs | Bark | Otherwise burned | 0.97 | (69) |
| | | Landscaping | 0.08 | (69) |
| Veneer logs | Bark | Otherwise burned | 0.92 | (69) |
| | | Landscaping | 0.08 | (69) |
| | Coarse residue | Fiber product | 0.76 | (69) |
| | | Otherwise burned | 0.24 | (69) |
| | Fine residue | Landscaping | 0.02 | (69) |
| | | Fiber product | 0.07 | (69) |
| Pole logs | Bark | Otherwise burned | 0.91 | (69) |
| | | Landscaping | 0.65 | (69) |
| | | Fiber product | 0.01 | (69) |
| | Coarse residue | Otherwise burned | 0.34 | (69) |
| | | Landscaping | 0.15 | (69) |
| | | Miscellaneous | 0.08 | (69) |
| Bioenergy logs | Bark | Fiber product | 0.5 | (69) |
| | | Otherwise burned | 0.27 | (69) |
| | | Landscaping | 0.04 | (69) |
| Composite logs | Bark | Otherwise burned | 0.96 | (69) |
| | | Landscaping | 0.1 | (69) |
| | | Fiber product | 0.06 | (69) |
| | | Otherwise burned | 0.84 | (69) |

Table A20. "Fiber product" mill residue use.

| Residue Type | Use | Portion | Source |
|----------------|-----------------------|---------|--------|
| Bark | Paper | 0.181 | (167) |
| | Non-structural panels | 0.819 | (167) |
| Fine residue | Paper | 0.181 | (167) |
| | Non-structural panels | 0.819 | (167) |
| Coarse residue | Paper | 0.954 | (167) |
| | Non-structural panels | 0.046 | (167) |

Table A21. Specific gravity of loblolly pine wood.

| Parameter | Loblolly Pine | Source |
|------------------|---------------|--------|
| Specific gravity | 0.47 | (11) |

Table A22. Recycling parameters.

| Product Category | Parameter | Value | Source |
|-------------------------|--|-------|-----------|
| Shipping products | Portion of pallets recycled as pallets | 0.7 | (185) |
| | Number of times pallets are recycled | 3 | (185,190) |
| Pulp and paper products | Portion of corrugated boxes recycled as corrugated boxes | 0.914 | (104) |
| | Number of times corrugated boxes are recycled | 5 | (191) |
| | Portion of sanitary products recycled as sanitary products | 0 | (75) |
| | Number of times sanitary products are recycled | 5 | (191) |
| | Portion of packaging cartonboard recycled as packaging cartonboard | 0.208 | (75) |
| | Number of packaging cartonboard is recycled | 5 | (191) |
| | Portion of disposable food related products recycled as disposable food related products | 0 | (75) |
| | Number of times disposable food related products are recycled | 5 | (191) |
| | Portion of miscellaneous paper products recycled as miscellaneous paper products | 0.081 | (75,167) |
| | Number of times miscellaneous paper is recycled | 5 | (191) |

Table A23. Primary product carbon usage in housing (structural vs. non-structural).

| Housing Type | Primary Product | Structural | Non-Structural | Source |
|--------------------|-----------------------|------------|----------------|-----------------------|
| Single Family Home | Lumber | 0.926 | 0.074 | (165) |
| | Engineered wood | 1 | 0 | Professional judgment |
| | Structural panels | 0.992 | 0.008 | (165) |
| | Non-structural panels | 0.57 | 0.43 | (165) |
| Multi-Family Home | Poles and pilings | 1 | 0 | Professional judgment |
| | Lumber | 0.924 | 0.076 | (165) |
| | Engineered wood | 1 | 0 | Professional judgment |
| | Structural panels | 0.982 | 0.018 | (165) |
| | Non-structural panels | 0.441 | 0.559 | (165) |
| | Poles and pilings | 1 | 0 | Professional judgment |

Table A24. Portion of structural housing carbon in each application.

| Primary Product | Application | Single Family | Multi-Family | Source |
|-----------------------|-------------|---------------|--------------|-----------------------|
| Softwood lumber | Floors | 0.109 | 0.188 | (166) |
| | Walls | 0.443 | 0.553 | (166) |
| | Roofs | 0.351 | 0.254 | (166) |
| | Foundations | 0.008 | 0.002 | (166) |
| | Decks | 0.088 | 0.003 | (166) |
| Engineered wood | Floors | 0.862 | 0.906 | (166) |
| | Walls | 0.089 | 0.059 | (166) |
| | Roofs | 0.049 | 0.035 | (166) |
| | Foundations | 0.000 | 0.000 | (166) |
| | Decks | 0.000 | 0.000 | (166) |
| Softwood plywood | Floors | 0.339 | 0.453 | (166) |
| | Walls | 0.203 | 0.118 | (166) |
| | Roofs | 0.455 | 0.429 | (166) |
| | Foundations | 0.003 | 0.000 | (166) |
| | Decks | 0.000 | 0.000 | (166) |
| OSB | Floors | 0.236 | 0.427 | (166) |
| | Walls | 0.340 | 0.153 | (166) |
| | Roofs | 0.424 | 0.420 | (166) |
| | Foundations | 0.000 | 0.000 | (166) |
| | Decks | 0.000 | 0.000 | (166) |
| Non-structural panels | Floors | 0.918 | 0.563 | (166) |
| | Walls | 0.082 | 0.438 | (166) |
| | Roofs | 0.000 | 0.000 | (166) |
| | Foundations | 0.000 | 0.000 | (166) |
| | Decks | 0.000 | 0.000 | (166) |
| Poles and Pilings | Floors | 0.100 | 0.100 | Professional judgment |
| | Walls | 0.600 | 0.600 | Professional judgment |
| | Roofs | 0.100 | 0.100 | Professional judgment |
| | Foundations | 0.100 | 0.100 | Professional judgment |
| | Decks | 0.100 | 0.100 | Professional judgment |

Table A25. Portion of non-structural housing carbon in each application.

| Primary Product | Application | Single Family | Multi-Family | Source |
|--|----------------|---------------|--------------|-----------------------|
| Softwood lumber | Exterior doors | 0.059 | 0.045 | (165) |
| | Interior doors | 0.397 | 0.338 | (165) |
| | Garage doors | 0.046 | 0.030 | (165) |
| | Windows | 0.100 | 0.030 | (165) |
| | Moulding | 0.231 | 0.361 | (165) |
| | Shelving | 0.037 | 0.023 | (165) |
| | Cabinets | 0.130 | 0.173 | (165) |
| | Countertops | 0.000 | 0.000 | (165) |
| Engineered wood | Exterior doors | 0.000 | 0.000 | (165) |
| | Interior doors | 0.000 | 0.000 | (165) |
| | Garage doors | 0.000 | 0.000 | (165) |
| | Windows | 0.000 | 0.000 | (165) |
| | Moulding | 0.000 | 0.000 | (165) |
| | Shelving | 0.000 | 0.000 | (165) |
| | Cabinets | 0.000 | 0.000 | (165) |
| | Countertops | 0.000 | 0.000 | (165) |
| Structural panels (OSB and softwood plywood) | Exterior doors | 0.034 | 0.042 | (165) |
| | Interior doors | 0.171 | 0.208 | (165) |
| | Garage doors | 0.078 | 0.042 | (165) |
| | Windows | 0.000 | 0.000 | (165) |
| | Moulding | 0.000 | 0.000 | (165) |
| | Shelving | 0.410 | 0.458 | (165) |
| | Cabinets | 0.000 | 0.000 | (165) |
| | Countertops | 0.307 | 0.250 | (165) |
| Non-structural panels | Exterior doors | 0.096 | 0.030 | (165) |
| | Interior doors | 0.212 | 0.077 | (165) |
| | Garage doors | 0.072 | 0.012 | (165) |
| | Windows | 0.000 | 0.000 | (165) |
| | Moulding | 0.000 | 0.000 | (165) |
| | Shelving | 0.108 | 0.098 | (165) |
| | Cabinets | 0.256 | 0.692 | (165) |
| | Countertops | 0.256 | 0.090 | (165) |
| Poles and Pilings | Exterior doors | 0.000 | 0.000 | Professional judgment |
| | Interior doors | 0.000 | 0.000 | Professional judgment |
| | Garage doors | 0.000 | 0.000 | Professional judgment |
| | Windows | 0.300 | 0.300 | Professional judgment |
| | Moulding | 0.700 | 0.700 | Professional judgment |
| | Shelving | 0.000 | 0.000 | Professional judgment |
| | Cabinets | 0.000 | 0.000 | Professional judgment |
| | Countertops | 0.000 | 0.000 | Professional judgment |

Tables A26-48. Results Tables

Table A26. Carbon storage and pulse emissions from loblolly and shortleaf pine timber harvested in 2020.

| Years Since Harvest | Total Storage In Use | Total Storage In Landfills | CO ₂ Emissions from Products | CO ₂ Emissions from Landfills | CH ₄ Emissions from Landfills |
|---------------------|----------------------|----------------------------|---|--|--|
| | MtC | MtC | MtCO _{2e} | MtCO _{2e} | MtCO _{2e} |
| 0 | 29.65 | 0.13 | -36.24 | 0.00 | 0.00 |
| 1 | 25.28 | 2.63 | -6.83 | 0.00 | 0.00 |
| 2 | 19.77 | 5.54 | -9.49 | -0.09 | -0.18 |
| 3 | 18.26 | 5.88 | -4.06 | -0.19 | -0.38 |
| 4 | 17.15 | 6.08 | -3.15 | -0.19 | -0.38 |
| 5 | 16.30 | 6.22 | -2.42 | -0.18 | -0.37 |
| 6 | 15.45 | 6.33 | -2.51 | -0.18 | -0.36 |
| 7 | 14.37 | 6.43 | -3.43 | -0.17 | -0.34 |
| 8 | 12.66 | 6.53 | -5.74 | -0.16 | -0.33 |
| 9 | 10.43 | 6.64 | -7.61 | -0.16 | -0.32 |
| 10 | 8.49 | 6.72 | -6.63 | -0.15 | -0.31 |
| 20 | 6.29 | 7.05 | -0.13 | -0.10 | -0.21 |
| 30 | 5.39 | 7.48 | -0.16 | -0.06 | -0.14 |
| 40 | 4.56 | 7.94 | -0.16 | -0.04 | -0.10 |
| 50 | 3.86 | 8.36 | -0.15 | -0.03 | -0.07 |
| 60 | 3.32 | 8.70 | -0.13 | -0.02 | -0.05 |
| 70 | 2.90 | 8.97 | -0.12 | -0.01 | -0.04 |
| 80 | 2.57 | 9.18 | -0.11 | -0.01 | -0.03 |
| 90 | 2.28 | 9.38 | -0.10 | -0.01 | -0.02 |
| 100 | 2.00 | 9.57 | -0.09 | 0.00 | -0.02 |
| 110 | 1.73 | 9.75 | -0.08 | 0.00 | -0.02 |
| 120 | 1.47 | 9.93 | -0.07 | 0.00 | -0.02 |

Table A27. Division of carbon from loblolly and shortleaf pine timber harvested in 2020 by primary product category.

| Primary Product | Carbon Division |
|-------------------------|-----------------|
| Lumber | 15.78% |
| Plywood | 2.52% |
| OSB | 2.68% |
| Non-structural panels | 1.53% |
| Engineered wood | 0.95% |
| Poles | 0.71% |
| Pulp and paper products | 47.58% |
| Landscaping | 2.30% |
| Bedding | 0.84% |
| Miscellaneous | 1.54% |
| Pellets | 7.72% |
| Otherwise Burned | 16.04% |

Table A28. Division of carbon from loblolly and shortleaf pine timber harvested in 2020 by secondary product category.

| Secondary Product | Carbon Division |
|--------------------------------------|------------------------|
| Single family homes | 6.89% |
| Multi-family homes | 1.06% |
| Manufactured home | 0.34% |
| Single family home upkeep | 4.84% |
| Multi-family home upkeep | 0.70% |
| Manufactured upkeep | 0.49% |
| Building | 1.01% |
| Other new structure | 0.49% |
| Other (non-residential upkeep, etc.) | 1.64% |
| Pallets | 2.26% |
| Other shipping | 0.52% |
| Poles | 0.25% |
| Posts/Pilings | 0.42% |
| Bedding | 0.84% |
| Landscaping | 2.30% |
| Corrugated boxes | 26.87% |
| Sanitary products | 10.53% |
| Packaging cardboard | 5.46% |
| Disposable food related products | 3.07% |
| Miscellaneous paper products | 1.65% |
| Furniture | 0.66% |
| Other manufacturing | 1.46% |
| Miscellaneous | 1.42% |
| Total In Use | 75.17% |

Table A29. Total carbon storage from 100 green tonnes of loblolly pine logs (tC).

| Years Since Harvest | Pulp Logs | CNS Logs | Saw Logs | Large Saw Logs | Veneer Logs | Pole Logs | Composite Logs | Bioenergy Logs |
|---------------------|-----------|----------|----------|----------------|-------------|-----------|----------------|----------------|
| 0 | 22.35 | 17.75 | 18.20 | 19.11 | 16.24 | 22.44 | 22.08 | 0.10 |
| 1 | 20.45 | 16.87 | 17.36 | 18.33 | 15.76 | 22.16 | 22.03 | 0.09 |
| 2 | 18.03 | 15.43 | 15.98 | 17.07 | 15.04 | 21.22 | 21.82 | 0.05 |
| 3 | 17.21 | 14.56 | 15.14 | 16.30 | 14.67 | 20.32 | 21.59 | 0.02 |
| 4 | 16.47 | 13.97 | 14.56 | 15.74 | 14.39 | 19.94 | 21.46 | 0.00 |
| 5 | 15.85 | 13.56 | 14.14 | 15.31 | 14.18 | 19.86 | 21.37 | 0.00 |
| 6 | 15.19 | 13.14 | 13.72 | 14.86 | 13.97 | 19.82 | 21.30 | 0.00 |
| 7 | 14.19 | 12.69 | 13.27 | 14.42 | 13.67 | 19.76 | 21.24 | 0.00 |
| 8 | 12.40 | 12.09 | 12.70 | 13.91 | 13.16 | 19.67 | 21.19 | 0.00 |
| 9 | 9.98 | 11.34 | 12.00 | 13.32 | 12.49 | 19.56 | 21.14 | 0.00 |
| 10 | 7.87 | 10.70 | 11.40 | 12.80 | 11.91 | 19.45 | 21.10 | 0.00 |
| 20 | 5.93 | 9.91 | 10.63 | 12.07 | 11.19 | 18.69 | 20.72 | 0.00 |
| 30 | 5.63 | 9.59 | 10.30 | 11.70 | 10.89 | 17.44 | 20.29 | 0.00 |
| 40 | 5.45 | 9.34 | 10.02 | 11.38 | 10.65 | 16.02 | 19.87 | 0.00 |
| 50 | 5.33 | 9.14 | 9.80 | 11.12 | 10.45 | 14.82 | 19.51 | 0.00 |
| 60 | 5.26 | 8.98 | 9.63 | 10.92 | 10.29 | 13.90 | 19.20 | 0.00 |
| 70 | 5.21 | 8.87 | 9.50 | 10.77 | 10.16 | 13.15 | 18.93 | 0.00 |
| 80 | 5.18 | 8.79 | 9.41 | 10.65 | 10.04 | 12.51 | 18.69 | 0.00 |
| 90 | 5.16 | 8.71 | 9.32 | 10.55 | 9.93 | 11.96 | 18.45 | 0.00 |
| 100 | 5.15 | 8.64 | 9.25 | 10.46 | 9.82 | 11.54 | 18.21 | 0.00 |
| 110 | 5.14 | 8.58 | 9.18 | 10.37 | 9.72 | 11.23 | 17.98 | 0.00 |
| 120 | 5.14 | 8.52 | 9.11 | 10.29 | 9.61 | 11.03 | 17.75 | 0.00 |

Table A30. Annual biogenic CO₂ pulse emissions from 100 green tonnes of loblolly pine logs (tCO₂e).

| Years Since Harvest | Pulp Logs | CNS Logs | Saw Logs | Large Saw Logs | Veneer Logs | Pole Logs | Composite Logs | Bioenergy Logs |
|---------------------|-----------|----------|----------|----------------|-------------|-----------|----------------|----------------|
| 0 | -9.79 | -26.65 | -24.99 | -21.67 | -32.18 | -9.45 | -10.74 | -91.43 |
| 1 | -6.96 | -3.21 | -3.09 | -2.85 | -1.78 | -1.03 | -0.26 | -0.03 |
| 2 | -8.85 | -5.31 | -5.09 | -4.65 | -2.66 | -3.42 | -0.82 | -0.13 |
| 3 | -2.96 | -3.20 | -3.08 | -2.85 | -1.38 | -3.32 | -0.88 | -0.14 |
| 4 | -2.68 | -2.17 | -2.14 | -2.08 | -1.03 | -1.37 | -0.53 | -0.05 |
| 5 | -2.23 | -1.54 | -1.57 | -1.62 | -0.78 | -0.31 | -0.37 | -0.01 |
| 6 | -2.37 | -1.53 | -1.56 | -1.64 | -0.79 | -0.17 | -0.33 | 0.00 |
| 7 | -3.63 | -1.67 | -1.66 | -1.64 | -1.11 | -0.22 | -0.27 | 0.00 |
| 8 | -6.53 | -2.23 | -2.12 | -1.90 | -1.86 | -0.34 | -0.23 | 0.00 |
| 9 | -8.82 | -2.74 | -2.57 | -2.21 | -2.47 | -0.44 | -0.22 | 0.00 |
| 10 | -7.73 | -2.38 | -2.22 | -1.91 | -2.17 | -0.43 | -0.21 | 0.00 |
| 20 | -0.12 | -0.17 | -0.19 | -0.21 | -0.16 | -0.58 | -0.24 | 0.00 |
| 30 | -0.07 | -0.18 | -0.20 | -0.23 | -0.18 | -1.14 | -0.31 | 0.00 |
| 40 | -0.05 | -0.17 | -0.18 | -0.22 | -0.16 | -1.74 | -0.30 | 0.00 |
| 50 | -0.03 | -0.14 | -0.15 | -0.18 | -0.14 | -2.36 | -0.27 | 0.00 |
| 60 | -0.02 | -0.10 | -0.12 | -0.14 | -0.11 | -2.95 | -0.23 | 0.00 |
| 70 | -0.01 | -0.08 | -0.09 | -0.11 | -0.09 | -3.38 | -0.20 | 0.00 |
| 80 | -0.01 | -0.06 | -0.07 | -0.08 | -0.08 | -3.51 | -0.18 | 0.00 |
| 90 | 0.00 | -0.05 | -0.06 | -0.07 | -0.08 | -3.31 | -0.18 | 0.00 |
| 100 | 0.00 | -0.05 | -0.05 | -0.07 | -0.08 | -2.84 | -0.18 | 0.00 |
| 110 | 0.00 | -0.04 | -0.05 | -0.06 | -0.08 | -2.23 | -0.18 | 0.00 |
| 120 | 0.00 | -0.04 | -0.05 | -0.06 | -0.08 | -1.59 | -0.17 | 0.00 |

Table A31. Annual biogenic CH₄ pulse emissions from 100 green tonnes of loblolly pine logs (tCO_{2e}).

| Years Since Harvest | Pulp Logs | CNS Logs | Saw Logs | Large Saw Logs | Veneer Logs | Pole Logs | Composite Logs | Bioenergy Logs |
|---------------------|-----------|----------|----------|----------------|-------------|-----------|----------------|----------------|
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.00 |
| 2 | -0.21 | -0.06 | -0.05 | -0.04 | -0.05 | -0.01 | -0.01 | 0.00 |
| 3 | -0.45 | -0.12 | -0.11 | -0.09 | -0.10 | -0.01 | -0.01 | 0.00 |
| 4 | -0.45 | -0.12 | -0.11 | -0.09 | -0.11 | -0.01 | -0.01 | 0.00 |
| 5 | -0.44 | -0.11 | -0.11 | -0.09 | -0.10 | -0.01 | -0.01 | 0.00 |
| 6 | -0.42 | -0.11 | -0.10 | -0.09 | -0.10 | -0.01 | -0.01 | 0.00 |
| 7 | -0.41 | -0.11 | -0.10 | -0.08 | -0.10 | -0.01 | -0.01 | 0.00 |
| 8 | -0.39 | -0.10 | -0.10 | -0.08 | -0.09 | -0.01 | -0.01 | 0.00 |
| 9 | -0.38 | -0.10 | -0.09 | -0.08 | -0.09 | -0.01 | -0.01 | 0.00 |
| 10 | -0.36 | -0.10 | -0.09 | -0.08 | -0.09 | -0.01 | -0.01 | 0.00 |
| 20 | -0.23 | -0.07 | -0.07 | -0.06 | -0.06 | -0.02 | -0.02 | 0.00 |
| 30 | -0.15 | -0.05 | -0.05 | -0.05 | -0.05 | -0.04 | -0.03 | 0.00 |
| 40 | -0.09 | -0.04 | -0.04 | -0.04 | -0.04 | -0.06 | -0.04 | 0.00 |
| 50 | -0.06 | -0.04 | -0.04 | -0.04 | -0.03 | -0.07 | -0.04 | 0.00 |
| 60 | -0.04 | -0.03 | -0.03 | -0.04 | -0.03 | -0.06 | -0.04 | 0.00 |
| 70 | -0.02 | -0.03 | -0.03 | -0.03 | -0.03 | -0.06 | -0.04 | 0.00 |
| 80 | -0.01 | -0.02 | -0.02 | -0.03 | -0.02 | -0.05 | -0.04 | 0.00 |
| 90 | -0.01 | -0.02 | -0.02 | -0.02 | -0.02 | -0.04 | -0.04 | 0.00 |
| 100 | -0.01 | -0.02 | -0.02 | -0.02 | -0.02 | -0.03 | -0.04 | 0.00 |
| 110 | 0.00 | -0.01 | -0.02 | -0.02 | -0.02 | -0.03 | -0.04 | 0.00 |
| 120 | 0.00 | -0.01 | -0.01 | -0.02 | -0.02 | -0.02 | -0.04 | 0.00 |

Table A32. Total biogenic and fossil fuel annual pulse emissions from 100 green tonnes of loblolly pine logs (tCO_{2e}).

| Years Since Harvest | Pulp Logs | CNS Logs | Saw Logs | Large Saw Logs | Veneer Logs | Pole Logs | Composite Logs | Bioenergy Logs |
|---------------------|-----------|----------|----------|----------------|-------------|-----------|----------------|----------------|
| 0 | -52.07 | -44.23 | -42.17 | -38.05 | -54.70 | -20.10 | -31.18 | -98.59 |
| 1 | -6.96 | -3.21 | -3.09 | -2.85 | -1.78 | -1.03 | -0.26 | -0.03 |
| 2 | -9.07 | -5.36 | -5.14 | -4.69 | -2.72 | -3.43 | -0.83 | -0.13 |
| 3 | -3.41 | -3.31 | -3.19 | -2.94 | -1.49 | -3.33 | -0.89 | -0.14 |
| 4 | -3.12 | -2.28 | -2.25 | -2.17 | -1.14 | -1.38 | -0.54 | -0.05 |
| 5 | -2.67 | -1.66 | -1.67 | -1.71 | -0.88 | -0.33 | -0.38 | -0.01 |
| 6 | -2.80 | -1.64 | -1.67 | -1.73 | -0.89 | -0.18 | -0.34 | 0.00 |
| 7 | -4.03 | -1.78 | -1.76 | -1.72 | -1.20 | -0.23 | -0.28 | 0.00 |
| 8 | -6.92 | -2.33 | -2.22 | -1.99 | -1.96 | -0.35 | -0.24 | 0.00 |
| 9 | -9.20 | -2.84 | -2.66 | -2.29 | -2.56 | -0.46 | -0.23 | 0.00 |
| 10 | -8.09 | -2.48 | -2.32 | -1.99 | -2.26 | -0.45 | -0.22 | 0.00 |
| 20 | -0.35 | -0.25 | -0.25 | -0.27 | -0.22 | -0.60 | -0.26 | 0.00 |
| 30 | -0.22 | -0.24 | -0.25 | -0.28 | -0.23 | -1.18 | -0.34 | 0.00 |
| 40 | -0.14 | -0.21 | -0.23 | -0.26 | -0.20 | -1.80 | -0.34 | 0.00 |
| 50 | -0.09 | -0.17 | -0.19 | -0.22 | -0.17 | -2.42 | -0.31 | 0.00 |
| 60 | -0.06 | -0.13 | -0.15 | -0.18 | -0.14 | -3.01 | -0.28 | 0.00 |
| 70 | -0.03 | -0.10 | -0.11 | -0.14 | -0.12 | -3.43 | -0.24 | 0.00 |
| 80 | -0.02 | -0.08 | -0.09 | -0.11 | -0.11 | -3.56 | -0.22 | 0.00 |
| 90 | -0.01 | -0.07 | -0.08 | -0.10 | -0.10 | -3.35 | -0.22 | 0.00 |
| 100 | -0.01 | -0.06 | -0.07 | -0.09 | -0.10 | -2.88 | -0.22 | 0.00 |
| 110 | -0.01 | -0.06 | -0.07 | -0.08 | -0.10 | -2.25 | -0.21 | 0.00 |
| 120 | 0.00 | -0.06 | -0.06 | -0.08 | -0.09 | -1.62 | -0.21 | 0.00 |

Table A33a. Portion of primary product carbon remaining in use up to 120 years after production.

| Years Since Harvest | Lumber | Plywood | OSB | Non-Structural Panels | Engineered Wood |
|---------------------|--------|---------|-------|-----------------------|-----------------|
| 0 | 0.932 | 0.944 | 0.944 | 0.936 | 0.948 |
| 1 | 0.913 | 0.939 | 0.939 | 0.933 | 0.948 |
| 2 | 0.882 | 0.920 | 0.920 | 0.920 | 0.947 |
| 3 | 0.858 | 0.898 | 0.898 | 0.900 | 0.946 |
| 4 | 0.834 | 0.884 | 0.884 | 0.879 | 0.945 |
| 5 | 0.807 | 0.874 | 0.874 | 0.854 | 0.945 |
| 6 | 0.778 | 0.863 | 0.863 | 0.823 | 0.944 |
| 7 | 0.754 | 0.852 | 0.852 | 0.788 | 0.944 |
| 8 | 0.737 | 0.841 | 0.841 | 0.752 | 0.944 |
| 9 | 0.725 | 0.830 | 0.830 | 0.715 | 0.943 |
| 10 | 0.714 | 0.821 | 0.821 | 0.679 | 0.942 |
| 20 | 0.628 | 0.747 | 0.747 | 0.396 | 0.930 |
| 30 | 0.539 | 0.668 | 0.668 | 0.191 | 0.904 |
| 40 | 0.452 | 0.591 | 0.591 | 0.093 | 0.866 |
| 50 | 0.375 | 0.524 | 0.524 | 0.060 | 0.818 |
| 60 | 0.314 | 0.468 | 0.468 | 0.044 | 0.761 |
| 70 | 0.271 | 0.423 | 0.422 | 0.031 | 0.698 |
| 80 | 0.238 | 0.383 | 0.382 | 0.022 | 0.630 |
| 90 | 0.210 | 0.345 | 0.344 | 0.014 | 0.559 |
| 100 | 0.184 | 0.307 | 0.306 | 0.009 | 0.487 |
| 110 | 0.159 | 0.270 | 0.269 | 0.005 | 0.417 |
| 120 | 0.136 | 0.233 | 0.232 | 0.003 | 0.351 |

Some values for year 0 are less than 1 because of construction and manufacturing waste deductions.

Table A33b. Portion of primary product carbon remaining in use up to 120 years after production.

| Years Since Harvest | Poles | Pulp and Paper Products | Landscaping and Bedding | Miscellaneous |
|---------------------|-------|-------------------------|-------------------------|---------------|
| 0 | 0.948 | 1.000 | 1.000 | 0.920 |
| 1 | 0.948 | 0.789 | 0.806 | 0.905 |
| 2 | 0.948 | 0.539 | 0.400 | 0.832 |
| 3 | 0.947 | 0.493 | 0.121 | 0.688 |
| 4 | 0.946 | 0.458 | 0.016 | 0.495 |
| 5 | 0.945 | 0.431 | 0.001 | 0.302 |
| 6 | 0.942 | 0.402 | 0.000 | 0.152 |
| 7 | 0.940 | 0.358 | 0.000 | 0.062 |
| 8 | 0.936 | 0.277 | 0.000 | 0.020 |
| 9 | 0.932 | 0.166 | 0.000 | 0.005 |
| 10 | 0.927 | 0.069 | 0.000 | 0.001 |
| 20 | 0.826 | 0.000 | 0.000 | 0.000 |
| 30 | 0.652 | 0.000 | 0.000 | 0.000 |
| 40 | 0.468 | 0.000 | 0.000 | 0.000 |
| 50 | 0.334 | 0.000 | 0.000 | 0.000 |
| 60 | 0.253 | 0.000 | 0.000 | 0.000 |
| 70 | 0.200 | 0.000 | 0.000 | 0.000 |
| 80 | 0.156 | 0.000 | 0.000 | 0.000 |
| 90 | 0.116 | 0.000 | 0.000 | 0.000 |
| 100 | 0.082 | 0.000 | 0.000 | 0.000 |
| 110 | 0.055 | 0.000 | 0.000 | 0.000 |
| 120 | 0.035 | 0.000 | 0.000 | 0.000 |

Some values for year 0 are less than 1 because of construction and manufacturing waste deductions.

Table A34a. Portion of primary product carbon remaining in landfills up to 120 years after production.

| Years Since Harvest | Lumber | Plywood | OSB | Non-Structural Panels | Engineered Wood |
|----------------------------|---------------|----------------|------------|------------------------------|------------------------|
| 0 | 0.012 | 0.019 | 0.019 | 0.000 | 0.031 |
| 1 | 0.013 | 0.022 | 0.022 | 0.002 | 0.031 |
| 2 | 0.018 | 0.036 | 0.036 | 0.013 | 0.031 |
| 3 | 0.023 | 0.051 | 0.051 | 0.027 | 0.031 |
| 4 | 0.029 | 0.060 | 0.060 | 0.043 | 0.031 |
| 5 | 0.034 | 0.067 | 0.067 | 0.063 | 0.031 |
| 6 | 0.041 | 0.074 | 0.074 | 0.086 | 0.031 |
| 7 | 0.049 | 0.082 | 0.082 | 0.114 | 0.032 |
| 8 | 0.057 | 0.091 | 0.091 | 0.142 | 0.032 |
| 9 | 0.065 | 0.099 | 0.099 | 0.172 | 0.033 |
| 10 | 0.073 | 0.107 | 0.107 | 0.200 | 0.033 |
| 20 | 0.138 | 0.163 | 0.163 | 0.418 | 0.043 |
| 30 | 0.205 | 0.223 | 0.223 | 0.572 | 0.062 |
| 40 | 0.271 | 0.280 | 0.280 | 0.646 | 0.091 |
| 50 | 0.329 | 0.331 | 0.331 | 0.670 | 0.128 |
| 60 | 0.374 | 0.372 | 0.373 | 0.681 | 0.171 |
| 70 | 0.407 | 0.406 | 0.407 | 0.689 | 0.218 |
| 80 | 0.431 | 0.436 | 0.436 | 0.695 | 0.269 |
| 90 | 0.452 | 0.464 | 0.465 | 0.700 | 0.323 |
| 100 | 0.470 | 0.492 | 0.493 | 0.703 | 0.377 |
| 110 | 0.489 | 0.520 | 0.521 | 0.705 | 0.429 |
| 120 | 0.506 | 0.547 | 0.548 | 0.706 | 0.479 |

Table A34b. Portion of primary product carbon remaining in landfills up to 120 years after production.

| Years Since Harvest | Poles | Pulp and Paper Products | Landscaping and Bedding | Miscellaneous |
|----------------------------|--------------|--------------------------------|--------------------------------|----------------------|
| 0 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1 | 0.000 | 0.127 | 0.062 | 0.012 |
| 2 | 0.000 | 0.272 | 0.131 | 0.070 |
| 3 | 0.001 | 0.282 | 0.134 | 0.186 |
| 4 | 0.001 | 0.284 | 0.134 | 0.340 |
| 5 | 0.002 | 0.283 | 0.134 | 0.495 |
| 6 | 0.004 | 0.282 | 0.134 | 0.614 |
| 7 | 0.006 | 0.280 | 0.134 | 0.686 |
| 8 | 0.008 | 0.280 | 0.134 | 0.719 |
| 9 | 0.011 | 0.280 | 0.133 | 0.731 |
| 10 | 0.015 | 0.281 | 0.133 | 0.734 |
| 20 | 0.084 | 0.262 | 0.133 | 0.731 |
| 30 | 0.203 | 0.249 | 0.132 | 0.727 |
| 40 | 0.326 | 0.241 | 0.132 | 0.725 |
| 50 | 0.411 | 0.236 | 0.131 | 0.723 |
| 60 | 0.455 | 0.232 | 0.131 | 0.722 |
| 70 | 0.478 | 0.230 | 0.131 | 0.720 |
| 80 | 0.492 | 0.229 | 0.131 | 0.719 |
| 90 | 0.502 | 0.228 | 0.131 | 0.719 |
| 100 | 0.509 | 0.228 | 0.131 | 0.718 |
| 110 | 0.513 | 0.227 | 0.131 | 0.717 |
| 120 | 0.516 | 0.227 | 0.130 | 0.717 |

Table A35a. Portion of primary product carbon remaining in use and in landfills up to 120 years after production.

| Years Since Harvest | Lumber | Plywood | OSB | Non-Structural Panels | Engineered Wood |
|----------------------------|---------------|----------------|------------|------------------------------|------------------------|
| 0 | 0.944 | 0.962 | 0.962 | 0.936 | 0.978 |
| 1 | 0.926 | 0.961 | 0.961 | 0.936 | 0.977 |
| 2 | 0.899 | 0.955 | 0.955 | 0.932 | 0.976 |
| 3 | 0.881 | 0.949 | 0.949 | 0.928 | 0.975 |
| 4 | 0.861 | 0.944 | 0.944 | 0.922 | 0.975 |
| 5 | 0.841 | 0.940 | 0.940 | 0.916 | 0.975 |
| 6 | 0.819 | 0.936 | 0.936 | 0.909 | 0.975 |
| 7 | 0.802 | 0.933 | 0.933 | 0.902 | 0.975 |
| 8 | 0.794 | 0.931 | 0.931 | 0.894 | 0.975 |
| 9 | 0.789 | 0.929 | 0.929 | 0.886 | 0.975 |
| 10 | 0.786 | 0.927 | 0.927 | 0.878 | 0.975 |
| 20 | 0.764 | 0.909 | 0.909 | 0.811 | 0.973 |
| 30 | 0.742 | 0.888 | 0.888 | 0.759 | 0.966 |
| 40 | 0.720 | 0.869 | 0.869 | 0.736 | 0.956 |
| 50 | 0.701 | 0.853 | 0.853 | 0.729 | 0.944 |
| 60 | 0.687 | 0.839 | 0.839 | 0.724 | 0.930 |
| 70 | 0.676 | 0.828 | 0.828 | 0.720 | 0.915 |
| 80 | 0.668 | 0.818 | 0.818 | 0.716 | 0.898 |
| 90 | 0.661 | 0.808 | 0.808 | 0.714 | 0.880 |
| 100 | 0.654 | 0.798 | 0.798 | 0.712 | 0.862 |
| 110 | 0.647 | 0.789 | 0.788 | 0.710 | 0.845 |
| 120 | 0.641 | 0.779 | 0.779 | 0.709 | 0.828 |

Some values for year 0 are less than 1 because of construction and manufacturing waste deductions.

Table A35b. Portion of primary product carbon remaining in use and in landfills up to 120 years after production.

| Years Since Harvest | Poles | Pulp and Paper Products | Landscaping and Bedding | Miscellaneous |
|----------------------------|--------------|--------------------------------|--------------------------------|----------------------|
| 0 | 0.948 | 1.000 | 1.000 | 0.920 |
| 1 | 0.948 | 0.916 | 0.868 | 0.917 |
| 2 | 0.948 | 0.810 | 0.531 | 0.903 |
| 3 | 0.948 | 0.775 | 0.255 | 0.874 |
| 4 | 0.947 | 0.742 | 0.150 | 0.835 |
| 5 | 0.947 | 0.714 | 0.135 | 0.797 |
| 6 | 0.946 | 0.684 | 0.134 | 0.766 |
| 7 | 0.945 | 0.638 | 0.134 | 0.748 |
| 8 | 0.944 | 0.557 | 0.134 | 0.739 |
| 9 | 0.943 | 0.446 | 0.133 | 0.736 |
| 10 | 0.941 | 0.350 | 0.133 | 0.735 |
| 20 | 0.907 | 0.262 | 0.133 | 0.731 |
| 30 | 0.846 | 0.249 | 0.132 | 0.727 |
| 40 | 0.776 | 0.241 | 0.132 | 0.725 |
| 50 | 0.717 | 0.236 | 0.131 | 0.723 |
| 60 | 0.672 | 0.232 | 0.131 | 0.722 |
| 70 | 0.635 | 0.230 | 0.131 | 0.720 |
| 80 | 0.603 | 0.229 | 0.131 | 0.719 |
| 90 | 0.576 | 0.228 | 0.131 | 0.719 |
| 100 | 0.555 | 0.228 | 0.131 | 0.718 |
| 110 | 0.540 | 0.227 | 0.131 | 0.717 |
| 120 | 0.530 | 0.227 | 0.130 | 0.717 |

Some values for year 0 are less than 1 because of construction and manufacturing waste deductions.

Table A36. Sensitivity of emissions from loblolly and shortleaf pine wood products to all tested parameters.

| Ranking | Parameter | Bounds | Units | μ | μ^* | σ |
|---------|---|-----------------|--|--------|---------|----------|
| 1 | DOC _f for paper in MSW landfills | 0.25 - 0.93 | portion | -16.68 | 16.68 | 4.49 |
| 2 | portion of CH ₄ recovered (R) in MSW landfills | 0.4019 - 0.8019 | portion | 9.62 | 9.62 | 4.71 |
| 3 | lifespan of corrugated boxes | 0.5 - 3 | years | 8.29 | 8.29 | 1.5 |
| 4 | downcycling to non-structural manufacturing of C&D waste | 0 - 0.129 | portion | -4.84 | 4.84 | 1.35 |
| 5 | production FF for pulp and paper | 0.3746 - 0.4579 | tCO ₂ e emitted/ tCO ₂ e in product | -4.81 | 4.81 | 0.29 |
| 6 | portion of CH ₄ oxidized (OX) in MSW landfills | 0.0221 - 0.4221 | portion | 4.73 | 4.73 | 2.67 |
| 7 | average sawmill efficiency | 0.3 - 0.5 | portion | 4.45 | 4.45 | 1.11 |
| 8 | DOC _f for wood in C&D landfills | 0 - 0.5 | portion | -4.19 | 4.19 | 1.16 |
| 9 | recycling rate for corrugated boxes | 0.814 - 1 | portion | 3.98 | 3.98 | 2.12 |
| 10 | recycling times for corrugated boxes | 3 - 7 | times | 3.97 | 3.97 | 2.46 |
| 11 | lifespan of single family home upkeep | 12 - 62 | years | 2.77 | 2.77 | 1.1 |
| 12 | pulp mill efficiency | 0.79 - 0.99 | portion | -2.68 | 2.68 | 1.23 |
| 13 | construction waste | 0 - 0.156 | portion | -2.61 | 2.61 | 0.44 |
| 14 | DOC _f for wood in MSW landfills | 0 - 0.5 | portion | -2.49 | 2.49 | 0.71 |
| 15 | half-life of landfilled paper | 12 - 18 | years | 2.4 | 2.4 | 1.21 |
| 16 | landfill rate of sanitary products | 0.456 - 0.856 | portion | 0.94 | 1.48 | 1.51 |
| 17 | downcycling to non-structural manufacturing of pallets | 0 - 0.1 | portion | -1.37 | 1.37 | 0.4 |
| 18 | landfill rate of corrugated boxes | 0 - 0.128 | portion | 0.16 | 1.15 | 1.43 |
| 19 | portion of product used for engineered wood | 0 - +20 | portion, change in portion | -1.14 | 1.14 | 0.71 |
| 20 | landfill rate of C&D waste | 0.522 - 0.922 | portion | 1.06 | 1.11 | 1.02 |
| 21 | landfill rate of packaging cartonboard | 0.44 - 0.84 | portion | 0.24 | 1.01 | 1.21 |
| 22 | shape factor (<i>k</i>) for weibull distribution | 2.1 - 3.16 | -- | -0.95 | 0.95 | 0.51 |
| 23 | lifespan of sanitary products | 0.5 - 3 | years | 0.91 | 0.91 | 0.33 |
| 24 | lifespan of other construction | 7 - 35 | years | 0.9 | 0.9 | 0.4 |
| 25 | transportation FF for pulp and paper | 0.0435 - 0.0587 | tCO ₂ e emitted/ tCO ₂ e in product | -0.86 | 0.86 | 0.05 |
| 26 | manufacturing waste | 0 - 0.28 | portion | -0.81 | 0.81 | 0.27 |
| 27 | veneer mill efficiency | 0.31 - 0.51 | portion | 0.76 | 0.76 | 0.15 |
| 28 | half-life of landfilled wood | 24 - 36 | years | 0.74 | 0.74 | 0.43 |
| 29 | landfill rate of furniture | 0.601 - 1 | portion | -0.73 | 0.73 | 0.43 |
| 30 | portion of coarse fiber res to composites | 0 - 0.146 | portion | 0.65 | 0.65 | 0.29 |
| 31 | procurement FF for pulp and paper | 0.048 - 0.0587 | tCO ₂ e emitted/ tCO ₂ e in product | -0.61 | 0.61 | 0.04 |
| 32 | portion of CH ₄ oxidized (OX) in C&D landfills | 0 - 0.3 | portion | 0.6 | 0.6 | 0.49 |
| 33 | downcycling to bedding rate of C&D waste | 0 - 0.1 | portion | -0.58 | 0.58 | 0.42 |

Table A36 (continued).

| | | | | | | |
|----|---|-----------------|--|-------|------|------|
| 34 | lifespan of packaging cartonboard | 0.5 - 3 | years | 0.58 | 0.58 | 0.25 |
| 35 | lifespan of furniture | 10.4 - 15.6 | years | -0.56 | 0.56 | 0.39 |
| 36 | lifespan of pallets | 0.5 - 3 | years | 0.5 | 0.5 | 0.15 |
| 37 | landfill rate of disposable food paper | 0.619 - 1 | portion | 0.05 | 0.48 | 0.62 |
| 38 | lifespan of bedding | 0.5 - 3 | years | -0.48 | 0.48 | 0.3 |
| 39 | portion of CH ₄ recovered (R) in C&D landfills | 0 - 0.2 | portion | 0.46 | 0.46 | 0.3 |
| 40 | lifespan of other manufacturing | 5.6 - 8.4 | years | -0.44 | 0.44 | 0.28 |
| 41 | landfill rate of miscellaneous | 0.601 - 1 | portion | 0.42 | 0.42 | 0.14 |
| 42 | lifespan of single family home | 100 - 150 | years | 0.41 | 0.41 | 0.23 |
| 43 | lifespan of multi-family home upkeep | 11 - 55 | years | 0.39 | 0.39 | 0.21 |
| 44 | landfill rate of other manufacturing | 0.601 - 1 | portion | -0.34 | 0.39 | 0.36 |
| 45 | composite mill efficiency | 0.8 - 1 | portion | 0.35 | 0.35 | 0.08 |
| 46 | production FF for lumber | 0.0794 - 0.097 | tCO ₂ e emitted/ tCO ₂ e in product | -0.35 | 0.35 | 0.06 |
| 47 | downcycling to non-structural manufacturing of other shipping | 0 - 0.1 | portion | -0.34 | 0.34 | 0.07 |
| 48 | downcycling to posts/pilings of poles | 0.209 - 0.609 | portion | -0.31 | 0.31 | 0.1 |
| 49 | lifespan of manufactured home upkeep | 7 - 35 | years | 0.29 | 0.29 | 0.14 |
| 50 | landfill rate of landscaping | 0 - 0.2 | portion | 0 | 0.27 | 0.33 |
| 51 | lifespan of disposable food paper | 0.5 - 3 | years | 0.26 | 0.26 | 0.09 |
| 52 | recycling times for pallets | 1 - 5 | times | 0.25 | 0.25 | 0.16 |
| 53 | landfill rate of miscellaneous paper | 0.378 - 0.778 | portion | 0.1 | 0.25 | 0.29 |
| 54 | lifespan of poles | 48 - 72 | years | 0.24 | 0.24 | 0.1 |
| 55 | recycling rate for packaging cartonboard | 0.008 - 0.408 | portion | 0.24 | 0.24 | 0.11 |
| 56 | landfill rate of bedding | 0.3 - 0.7 | portion | 0.01 | 0.24 | 0.29 |
| 57 | lifespan of landscaping | 1 - 4 | years | 0.01 | 0.21 | 0.25 |
| 58 | downcycling to bedding rate of pallets | 0 - 0.112 | portion | -0.2 | 0.2 | 0.16 |
| 59 | portion of fine fiber res to composites | 0.619 - 1 | portion | 0.18 | 0.2 | 0.16 |
| 60 | downcycling to landscaping rate of C&D waste | 0 - 0.161 | portion | -0.13 | 0.17 | 0.21 |
| 61 | production FF for pellets | 0.0781 - 0.0954 | tCO ₂ e emitted/ tCO ₂ e in product | -0.16 | 0.16 | 0.01 |
| 62 | production FF for engineered wood | 0.3511 - 0.4292 | tCO ₂ e emitted/tCO ₂ e in product | -0.16 | 0.16 | 0.19 |
| 63 | lifespan of miscellaneous paper | 0.5 - 3 | years | 0.16 | 0.16 | 0.04 |
| 64 | landfill rate of other shipping | 0.432 - 0.832 | portion | 0.15 | 0.15 | 0.05 |
| 65 | landfill rate of posts/pilings | 0.5 - 0.9 | portion | -0.15 | 0.15 | 0.09 |
| 66 | lifespan of buildings | 56 - 84 | years | 0.14 | 0.14 | 0.07 |
| 67 | landfill rate of pallets | 0 - 0.11 | portion | 0.13 | 0.13 | 0.06 |
| 68 | bioenergy mill efficiency | 0.8 - 1 | portion | -0.13 | 0.13 | 0.01 |
| 69 | recycling rate for pallets | 0.6 - 0.8 | portion | 0.13 | 0.13 | 0.09 |

Table A36 (continued).

| | | | | | | |
|-----|---|-----------------|--|-------|------|------|
| 70 | production FF for plywood | 0.1716 - 0.2097 | tCO ₂ e emitted/ tCO ₂ e in product | -0.13 | 0.13 | 0.02 |
| 71 | production FF for non- structural panels | 0.2124 - 0.2596 | tCO ₂ e emitted/ tCO ₂ e in product | -0.1 | 0.1 | 0.03 |
| 72 | lifespan of multi-family home | 88 - 132 | years | 0.09 | 0.09 | 0.05 |
| 73 | production FF for OSB | 0.1178 - 0.144 | tCO ₂ e emitted/ tCO ₂ e in product | -0.09 | 0.09 | 0.01 |
| 74 | recycling rate for sanitary products | 0 - 0.1 | portion | 0.09 | 0.09 | 0.05 |
| 75 | lifespan of miscellaneous | 2 - 6 | years | 0.09 | 0.09 | 0.04 |
| 76 | procurement FF for non- structural panels | 0.1806 - 0.2207 | tCO ₂ e emitted/ tCO ₂ e in product | -0.08 | 0.08 | 0.02 |
| 77 | downcycling to landscaping rate of pallets | 0.009 - 0.209 | portion | -0.07 | 0.08 | 0.09 |
| 78 | procurement FF for lumber | 0.0167 - 0.0204 | tCO ₂ e emitted/ tCO ₂ e in product | -0.07 | 0.07 | 0.01 |
| 79 | transportation FF for lumber | 0.0151 - 0.0184 | tCO ₂ e emitted/ tCO ₂ e in product | -0.06 | 0.06 | 0.01 |
| 80 | lifespan of other new structures | 48 - 72 | years | 0.06 | 0.06 | 0.03 |
| 81 | downcycling to bedding rate of other shipping | 0 - 0.1 | portion | -0.05 | 0.05 | 0.03 |
| 82 | lifespan of other shipping | 1 - 4 | years | 0.05 | 0.05 | 0.02 |
| 83 | procurement FF for OSB | 0.0618 - 0.0755 | tCO ₂ e emitted/ tCO ₂ e in product | -0.05 | 0.05 | 0 |
| 84 | lifespan of single family home parts unconnected | -0.4 | % change in years | 0.05 | 0.05 | 0.02 |
| 85 | procurement FF for plywood | 0.0644 - 0.0787 | tCO ₂ e emitted/ tCO ₂ e in product | -0.05 | 0.05 | 0.01 |
| 86 | pole mill efficiency | 0.71 - 0.91 | portion | 0.02 | 0.05 | 0.05 |
| 87 | recycling rate for miscellaneous paper | 0 - 0.281 | portion | 0.04 | 0.04 | 0.02 |
| 88 | downcycling to landscaping rate of other shipping | 0 - 0.338 | portion | -0.04 | 0.04 | 0.04 |
| 89 | lifespan of manufactured home | 56 - 84 | years | 0.04 | 0.04 | 0.02 |
| 90 | downcycling to non-structural manufacturing of poles | 0 - 0.1 | portion | -0.04 | 0.04 | 0.01 |
| 91 | lifespan of posts/pilings | 24 - 36 | years | -0.03 | 0.04 | 0.04 |
| 92 | production FF for poles | 0.0705 - 0.1058 | tCO ₂ e emitted/ tCO ₂ e in product | -0.03 | 0.03 | 0 |
| 93 | recycling rate for disposable food paper | 0 - 0.1 | portion | 0.02 | 0.02 | 0.01 |
| 94 | landfill rate of poles | 0.12 - 0.52 | portion | 0.01 | 0.01 | 0.01 |
| 95 | portion of bark fiber res to composites | 0.619 - 1 | portion | 0.01 | 0.01 | 0.01 |
| 96 | procurement FF for poles | 0.0149 - 0.0223 | tCO ₂ e emitted/ tCO ₂ e in product | -0.01 | 0.01 | 0 |
| 97 | transportation FF for plywood | 0.0086 - 0.0105 | tCO ₂ e emitted/ tCO ₂ e in product | -0.01 | 0.01 | 0 |
| 98 | transportation FF for poles | 0.0134 - 0.0201 | tCO ₂ e emitted/ tCO ₂ e in product | -0.01 | 0.01 | 0 |
| 99 | downcycling to bedding rate of poles | 0 - 0.1 | portion | 0 | 0 | 0 |
| 100 | transportation FF for OSB | 0.0054 - 0.0066 | tCO ₂ e emitted/ tCO ₂ e in product | 0 | 0 | 0 |

Table A36 (continued).

| | | | | | | |
|-----|---|-----------------|--|---|---|---|
| 101 | downcycling to landscaping rate of poles | 0 - 0.261 | portion | 0 | 0 | 0 |
| 102 | transportation FF for non-structural panels | 0.0051 - 0.0062 | tCO ₂ e emitted/ tCO ₂ e in product | 0 | 0 | 0 |
| 103 | recycling times for packaging cartonboard | 3 - 7 | times | 0 | 0 | 0 |
| 104 | lifespan of multi-family home parts unconnected | -0.4 | % change in years | 0 | 0 | 0 |
| 105 | recycling times for miscellaneous paper | 3 - 7 | times | 0 | 0 | 0 |
| 106 | recycling times for sanitary products | 3 - 7 | times | 0 | 0 | 0 |
| 107 | recycling times for disposable food paper | 3 - 7 | times | 0 | 0 | 0 |

DOC_f = the fraction of landfilled organic carbon that will decay over time; fiber res = mill residue that is used for a fiber product (pulp and paper or non-structural panels); MSW = municipal solid waste; C&D = construction and demolition; average sawmill efficiency = sawmill efficiency for 33-47 cm saw logs, with smaller logs having -0.05 efficiency and larger logs having +0.1 efficiency; FF = fossil fuel emission rate; the magnitude of μ^* indicates the influence of the parameter; the sign of μ indicates the direction of the effect; σ indicates interaction of the parameter with other parameters; the bounds indicate the tested range of parameter values (see section 2.3 of main text); the model output of which sensitivity was evaluated was the total (biogenic + fossil fuel) annual emission pulses from southwide loblolly and shortleaf pine harvested wood products produced over 120 years, discounted at 3%.

Table A37. Carbon storage from four silvicultural management scenarios, 60 years since initial planting (tC ha⁻¹).

| Silvicultural Regime | <i>In Situ</i> Carbon Storage | <i>Ex Situ</i> Carbon Storage | Total Carbon Storage |
|----------------------|-------------------------------|-------------------------------|----------------------|
| Pulp-20 | 83.85 | 10.91 | 94.76 |
| Pulp-24 | 114.2 | 20.61 | 134.81 |
| ST-20 | 90.95 | 12.07 | 103.02 |
| ST-24 | 105.45 | 16.88 | 122.33 |

Table A38. Carbon storage from four silvicultural management scenarios, 120 years since initial planting (tC ha⁻¹).

| Silvicultural Regime | <i>In Situ</i> Carbon Storage | <i>Ex Situ</i> Carbon Storage | Total Carbon Storage |
|----------------------|-------------------------------|-------------------------------|----------------------|
| Pulp-20 | 83.85 | 29.76 | 113.61 |
| Pulp-24 | 114.20 | 54.05 | 168.25 |
| ST-20 | 90.95 | 36.46 | 127.41 |
| ST-24 | 105.45 | 49.31 | 154.76 |

Table A39. Total carbon that enters the market or is burned by primary product for four silvicultural management scenarios (tC ha⁻¹).

| Primary Product | Pulp-20 | Pulp-24 | ST-20 | ST-24 |
|-------------------------|----------------|----------------|--------------|--------------|
| Lumber | 28.5 | 56.9 | 43.2 | 58.2 |
| Plywood | 7.1 | 11.4 | 8.0 | 10.4 |
| OSB | 9.5 | 12.9 | 8.5 | 11.0 |
| Non-structural panels | 3.4 | 6.5 | 4.8 | 6.3 |
| Engineered Wood | 2.4 | 3.9 | 2.8 | 3.7 |
| Poles | 2.3 | 3.4 | 2.3 | 3.0 |
| Pulp and paper products | 183.9 | 236.9 | 152.8 | 196.0 |
| Landscaping | 5.4 | 9.9 | 7.1 | 9.3 |
| Bedding | 1.8 | 3.6 | 2.6 | 3.4 |
| Miscellaneous | 3.3 | 6.5 | 4.8 | 6.3 |
| Pellets | -12.4 | -19.9 | -13.9 | -18.1 |
| Other burned | -45.5 | -71.5 | -49.5 | -64.3 |
| Total | 189.5 | 260.4 | 173.5 | 225.2 |

Includes six harvests for pulp regimes and four thins and final harvests for sawtimber regimes. Negative values indicate carbon (tC/ha) that was burned and, thus, emitted to the atmosphere.

Table A40. Total carbon that enters the market by secondary product category for four silvicultural management scenarios (tC ha⁻¹).

| Primary Product | Pulp-20 | Pulp-24 | ST-20 | ST-24 |
|------------------------------|----------------|----------------|--------------|--------------|
| New residential construction | 19.0 | 32.9 | 23.9 | 31.8 |
| Residential upkeep | 12.6 | 23.2 | 17.2 | 22.9 |
| Non-residential construction | 6.9 | 12.4 | 9.1 | 12.1 |
| Shipping | 5.4 | 10.3 | 7.7 | 10.4 |
| Poles, posts, and pilings | 2.2 | 3.2 | 2.2 | 2.8 |
| Bedding and landscaping | 7.1 | 13.4 | 9.8 | 12.8 |
| Corrugated boxes | 103.1 | 133.5 | 86.3 | 110.7 |
| Sanitary Products | 41.1 | 52.6 | 33.8 | 43.4 |
| Packaging cartonboard | 21.5 | 27.4 | 17.6 | 22.5 |
| Other pulp and paper | 18.1 | 23.4 | 15.1 | 19.4 |
| Manufacturing | 4.6 | 8.4 | 6.2 | 8.2 |
| Miscellaneous | 3.0 | 6.0 | 4.4 | 5.8 |

Includes six harvests for pulp regimes and four thins and final harvests for sawtimber regimes.

Table A41. Carbon storage in use from three wood usage scenarios and a business as usual (BAU) scenario (MtC).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | 29.65 | 29.49 | 29.66 | 23.47 |
| 1 | 25.28 | 25.09 | 26.16 | 20.37 |
| 2 | 19.77 | 19.52 | 21.56 | 16.36 |
| 3 | 18.26 | 18.00 | 20.24 | 15.15 |
| 4 | 17.15 | 16.88 | 19.28 | 14.26 |
| 5 | 16.30 | 16.02 | 18.61 | 13.58 |
| 6 | 15.45 | 15.17 | 18.01 | 12.90 |
| 7 | 14.37 | 14.08 | 17.49 | 12.08 |
| 8 | 12.66 | 12.35 | 17.01 | 10.84 |
| 9 | 10.43 | 10.10 | 16.56 | 9.26 |
| 10 | 8.49 | 8.14 | 16.12 | 7.88 |
| 20 | 6.29 | 5.97 | 6.51 | 6.11 |
| 30 | 5.39 | 5.14 | 5.71 | 5.23 |
| 40 | 4.56 | 4.35 | 4.93 | 4.43 |
| 50 | 3.86 | 3.68 | 4.24 | 3.75 |
| 60 | 3.32 | 3.16 | 3.66 | 3.22 |
| 70 | 2.90 | 2.77 | 3.20 | 2.82 |
| 80 | 2.57 | 2.46 | 2.85 | 2.50 |
| 90 | 2.28 | 2.17 | 2.55 | 2.21 |
| 100 | 2.00 | 1.91 | 2.28 | 1.94 |
| 110 | 1.73 | 1.65 | 2.02 | 1.68 |
| 120 | 1.47 | 1.41 | 1.78 | 1.44 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A42. Carbon storage in landfills from three wood usage scenarios and a business as usual (BAU) scenario (MtC).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | 0.13 | 0.12 | 0.11 | 0.12 |
| 1 | 2.63 | 2.65 | 2.03 | 1.87 |
| 2 | 5.54 | 5.58 | 4.30 | 3.92 |
| 3 | 5.88 | 5.93 | 4.61 | 4.19 |
| 4 | 6.08 | 6.14 | 4.82 | 4.37 |
| 5 | 6.22 | 6.28 | 4.97 | 4.51 |
| 6 | 6.33 | 6.40 | 5.11 | 4.63 |
| 7 | 6.43 | 6.51 | 5.22 | 4.73 |
| 8 | 6.53 | 6.61 | 5.31 | 4.83 |
| 9 | 6.64 | 6.72 | 5.39 | 4.93 |
| 10 | 6.72 | 6.81 | 5.45 | 5.01 |
| 20 | 7.05 | 7.09 | 6.02 | 5.43 |
| 30 | 7.48 | 7.47 | 6.42 | 5.91 |
| 40 | 7.94 | 7.91 | 6.91 | 6.40 |
| 50 | 8.36 | 8.30 | 7.39 | 6.84 |
| 60 | 8.70 | 8.62 | 7.80 | 7.19 |
| 70 | 8.97 | 8.87 | 8.14 | 7.45 |
| 80 | 9.18 | 9.07 | 8.41 | 7.67 |
| 90 | 9.38 | 9.26 | 8.63 | 7.86 |
| 100 | 9.57 | 9.44 | 8.84 | 8.05 |
| 110 | 9.75 | 9.61 | 9.03 | 8.23 |
| 120 | 9.93 | 9.78 | 9.22 | 8.41 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A43. Total carbon storage from three wood usage scenarios and a business as usual (BAU) scenario (MtC).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | 0.13 | 0.12 | 0.11 | 0.12 |
| 1 | 2.63 | 2.65 | 2.03 | 1.87 |
| 2 | 5.54 | 5.58 | 4.30 | 3.92 |
| 3 | 5.88 | 5.93 | 4.61 | 4.19 |
| 4 | 6.08 | 6.14 | 4.82 | 4.37 |
| 5 | 6.22 | 6.28 | 4.97 | 4.51 |
| 6 | 6.33 | 6.40 | 5.11 | 4.63 |
| 7 | 6.43 | 6.51 | 5.22 | 4.73 |
| 8 | 6.53 | 6.61 | 5.31 | 4.83 |
| 9 | 6.64 | 6.72 | 5.39 | 4.93 |
| 10 | 6.72 | 6.81 | 5.45 | 5.01 |
| 20 | 7.05 | 7.09 | 6.02 | 5.43 |
| 30 | 7.48 | 7.47 | 6.42 | 5.91 |
| 40 | 7.94 | 7.91 | 6.91 | 6.40 |
| 50 | 8.36 | 8.30 | 7.39 | 6.84 |
| 60 | 8.70 | 8.62 | 7.80 | 7.19 |
| 70 | 8.97 | 8.87 | 8.14 | 7.45 |
| 80 | 9.18 | 9.07 | 8.41 | 7.67 |
| 90 | 9.38 | 9.26 | 8.63 | 7.86 |
| 100 | 9.57 | 9.44 | 8.84 | 8.05 |
| 110 | 9.75 | 9.61 | 9.03 | 8.23 |
| 120 | 9.93 | 9.78 | 9.22 | 8.41 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A44. Biogenic CO₂ emissions from wood products (excluding landfills) from three wood usage scenarios and a business as usual (BAU) scenario (MtCO₂e).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | -36.24 | -36.85 | -36.30 | -58.89 |
| 1 | -6.83 | -6.88 | -5.87 | -4.98 |
| 2 | -9.49 | -9.57 | -8.54 | -7.15 |
| 3 | -4.06 | -4.10 | -3.61 | -3.32 |
| 4 | -3.15 | -3.16 | -2.66 | -2.48 |
| 5 | -2.42 | -2.41 | -1.80 | -1.86 |
| 6 | -2.51 | -2.50 | -1.60 | -1.91 |
| 7 | -3.43 | -3.44 | -1.41 | -2.52 |
| 8 | -5.74 | -5.78 | -1.34 | -4.06 |
| 9 | -7.61 | -7.67 | -1.32 | -5.33 |
| 10 | -6.63 | -6.69 | -1.34 | -4.65 |
| 20 | -0.13 | -0.12 | -0.37 | -0.13 |
| 30 | -0.16 | -0.15 | -0.39 | -0.16 |
| 40 | -0.16 | -0.15 | -0.42 | -0.16 |
| 50 | -0.15 | -0.14 | -0.39 | -0.15 |
| 60 | -0.13 | -0.12 | -0.34 | -0.13 |
| 70 | -0.12 | -0.11 | -0.28 | -0.12 |
| 80 | -0.11 | -0.10 | -0.24 | -0.10 |
| 90 | -0.10 | -0.09 | -0.20 | -0.10 |
| 100 | -0.09 | -0.08 | -0.19 | -0.09 |
| 110 | -0.08 | -0.07 | -0.17 | -0.08 |
| 120 | -0.07 | -0.06 | -0.16 | -0.07 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A45. Biogenic CO₂ emission pulses from landfills from three wood usage scenarios and a business as usual (BAU) scenario (MtCO₂e).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | -0.09 | -0.09 | -0.07 | -0.06 |
| 3 | -0.19 | -0.19 | -0.14 | -0.13 |
| 4 | -0.19 | -0.19 | -0.14 | -0.13 |
| 5 | -0.18 | -0.18 | -0.14 | -0.13 |
| 6 | -0.18 | -0.18 | -0.14 | -0.12 |
| 7 | -0.17 | -0.17 | -0.13 | -0.12 |
| 8 | -0.16 | -0.16 | -0.13 | -0.11 |
| 9 | -0.16 | -0.16 | -0.12 | -0.11 |
| 10 | -0.15 | -0.15 | -0.12 | -0.11 |
| 20 | -0.10 | -0.10 | -0.09 | -0.07 |
| 30 | -0.06 | -0.06 | -0.05 | -0.04 |
| 40 | -0.04 | -0.04 | -0.04 | -0.03 |
| 50 | -0.03 | -0.03 | -0.02 | -0.02 |
| 60 | -0.02 | -0.02 | -0.02 | -0.01 |
| 70 | -0.01 | -0.01 | -0.01 | -0.01 |
| 80 | -0.01 | -0.01 | -0.01 | -0.01 |
| 90 | -0.01 | -0.01 | -0.01 | 0.00 |
| 100 | 0.00 | 0.00 | 0.00 | 0.00 |
| 110 | 0.00 | 0.00 | 0.00 | 0.00 |
| 120 | 0.00 | 0.00 | 0.00 | 0.00 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A46. Biogenic CH₄ emission pulses from landfills from three wood usage scenarios and a business as usual (BAU) scenario (MtCO_{2e}).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | -0.18 | -0.18 | -0.14 | -0.12 |
| 3 | -0.38 | -0.38 | -0.29 | -0.26 |
| 4 | -0.38 | -0.38 | -0.29 | -0.26 |
| 5 | -0.37 | -0.37 | -0.29 | -0.25 |
| 6 | -0.36 | -0.36 | -0.28 | -0.25 |
| 7 | -0.34 | -0.35 | -0.27 | -0.24 |
| 8 | -0.33 | -0.33 | -0.26 | -0.23 |
| 9 | -0.32 | -0.32 | -0.25 | -0.22 |
| 10 | -0.31 | -0.31 | -0.24 | -0.21 |
| 20 | -0.21 | -0.21 | -0.18 | -0.14 |
| 30 | -0.14 | -0.14 | -0.12 | -0.10 |
| 40 | -0.10 | -0.10 | -0.08 | -0.07 |
| 50 | -0.07 | -0.07 | -0.06 | -0.05 |
| 60 | -0.05 | -0.05 | -0.04 | -0.04 |
| 70 | -0.04 | -0.04 | -0.03 | -0.03 |
| 80 | -0.03 | -0.03 | -0.03 | -0.03 |
| 90 | -0.02 | -0.02 | -0.02 | -0.02 |
| 100 | -0.02 | -0.02 | -0.02 | -0.02 |
| 110 | -0.02 | -0.02 | -0.02 | -0.02 |
| 120 | -0.02 | -0.01 | -0.01 | -0.01 |

CNS = chip-n-saw; reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A47. Fossil fuel emission pulses from procurement, transportation, and production from three wood usage scenarios and a business as usual (BAU) scenario (MtCO_{2e}).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | -43.33 | -43.66 | -43.33 | -34.09 |

Reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

Table A48. Total (biogenic + fossil fuel) emission pulses from three wood usage scenarios and a business as usual (BAU) scenario (MtCO_{2e}).

| Years Since Harvest | BAU | > CNS | > Lifespans | > Bioenergy |
|----------------------------|------------|-----------------|-----------------------|-----------------------|
| 0 | -79.57 | -80.51 | -79.62 | -92.98 |
| 1 | -6.83 | -6.88 | -5.88 | -4.98 |
| 2 | -9.76 | -9.84 | -8.74 | -7.34 |
| 3 | -4.62 | -4.67 | -4.04 | -3.70 |
| 4 | -3.71 | -3.73 | -3.10 | -2.86 |
| 5 | -2.97 | -2.96 | -2.23 | -2.24 |
| 6 | -3.04 | -3.03 | -2.01 | -2.28 |
| 7 | -3.95 | -3.96 | -1.81 | -2.87 |
| 8 | -6.23 | -6.28 | -1.73 | -4.40 |
| 9 | -8.08 | -8.15 | -1.70 | -5.66 |
| 10 | -7.10 | -7.16 | -1.70 | -4.97 |
| 20 | -0.44 | -0.43 | -0.63 | -0.34 |
| 30 | -0.37 | -0.36 | -0.56 | -0.30 |
| 40 | -0.30 | -0.29 | -0.53 | -0.26 |
| 50 | -0.25 | -0.23 | -0.47 | -0.22 |
| 60 | -0.20 | -0.19 | -0.40 | -0.19 |
| 70 | -0.17 | -0.16 | -0.33 | -0.16 |
| 80 | -0.15 | -0.14 | -0.27 | -0.14 |
| 90 | -0.13 | -0.12 | -0.23 | -0.12 |
| 100 | -0.11 | -0.11 | -0.21 | -0.11 |
| 110 | -0.10 | -0.09 | -0.19 | -0.10 |
| 120 | -0.09 | -0.08 | -0.18 | -0.08 |

Reference inputs for the scenarios were loblolly and shortleaf pine timber harvested in the southern US in 2020.

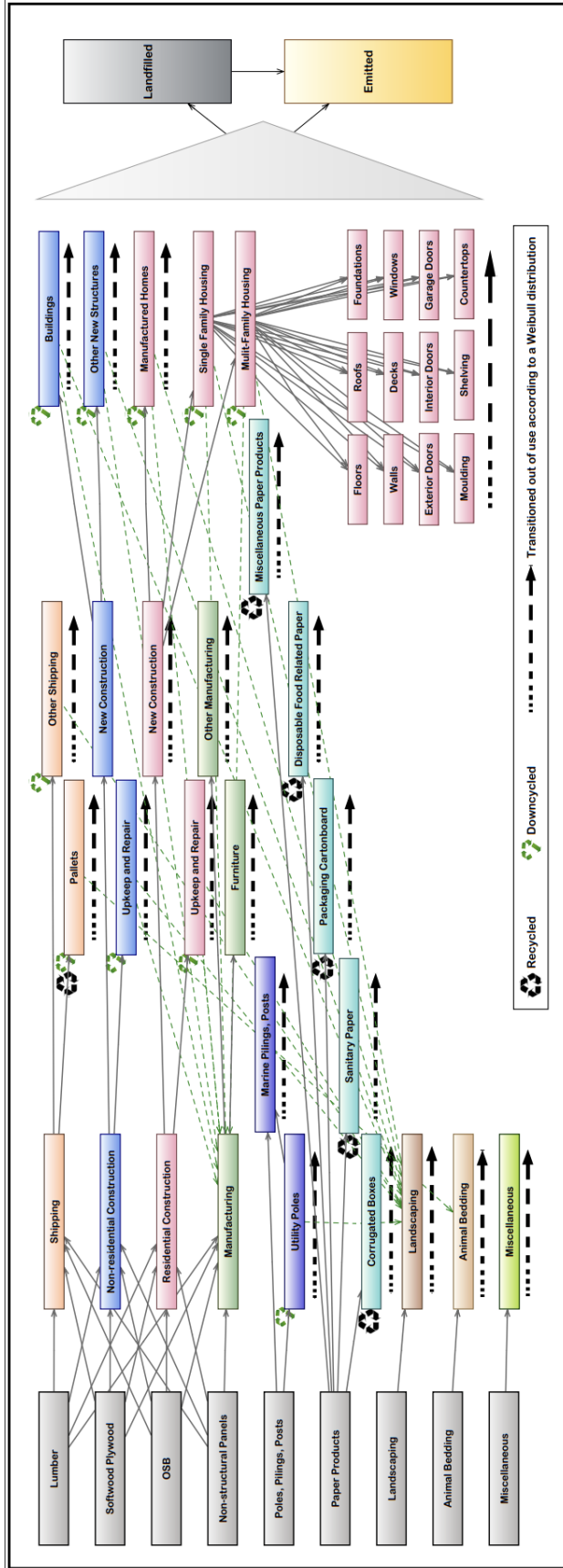


Figure A1. Flow of carbon from primary products to eventual emission. Shows the transition to secondary products, recycling, downcycling, landfilling, and emission.