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Special Issue
Forest Biomass, Carbon Neutrality, and Climate Change Mitigation

Edited by
Dr. Fabiano Ximenes

MDPI

https://doi.org/10.3390/f13091460

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Climate Smart Forestry in the Southern United States

Noah T. Shephard *, Lana Narine, Yucheng Peng and Adam Maggard

College of Forestry, Wildlife, and Environment, Auburn University, Auburn, AL 36380, USA
* Correspondence: nts0024@auburn.edu

Abstract: In the United States, Climate Smart Forestry (CSF) has quickly become a popular topic within the academic, political, and industry realms, without substantial delineation of what exactly CSF is. In this review, the aim is to provide a broad overview of CSF by highlighting one of the most productive and prolific forest systems in the United States, loblolly pine (*Pinus taeda* L.) plantations. One major objective of CSF is to increase forest carbon storage to combat rising atmospheric carbon or climate change mitigation. Fortuitously, increased forest carbon storage can work harmoniously with on-going Southern pine plantation forestry. With a Southern commercial focus, we show (1) traditional plantation practices such as genetic improvement, site preparation, weed control, and fertilization have aided increased forest carbon storage; (2) forest products and forest product carbon are essential to increase carbon storage beyond the stand-carbon baseline; (3) forest carbon data collection must be improved to realize climate change mitigation goals; and (4) additional avenues for future CSF research.

Keywords: climate change mitigation; climate change adaptation; monoculture; ecosystem services; carbon cycle

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Citation: Shephard, N.T.; Narine, L.; Peng, Y.; Maggard, A. Climate Smart Forestry in the Southern United States. *Forests* **2022**, *13*, 1460. https://doi.org/10.3390/f13091460

Academic Editor: Fabiano Ximenes

Received: 17 August 2022
Accepted: 7 September 2022
Published: 11 September 2022

1. Introduction

Southern plantation forests in the United States are one of the most globally productive timberland systems. Primarily composed of loblolly pine (*Pinus taeda* L.), Southern pine timberlands represent 22% (24 million ha) of total forest area and an astonishing 51% (218 thousand m^3 yr^{-1}) of total forest growth in the Southern region [1]. More broadly, loblolly pine is the second most abundant U.S. tree species (22 billion; red maple, *Acer rubrum* L., 25 billion) and represents an incredible 8% of nationwide live aboveground biomass (1.8 billion Mg yr^{-1}; 20% in South) [1]. Not surprisingly, vast productivity translates to Southern plantations accounting for 63% (178.8 million m^3 yr^{-1}) of nationwide softwood removals [1]. However, immense Southern pine productivity can be used effectively beyond traditional, economic goals. For example, fast-growing loblolly pine rotations, often less than 30 years, offer enormous potential to alleviate climate change effects, such as rising atmospheric carbon dioxide (CO_2), through the transfer of such atmospheric carbon to biomass carbon. Southern private forests account for almost 60% (61 Tg C yr^{-1}, circa 2018) of nationwide net aboveground biomass flux, a flux approximately 2.5 times greater than Northern private forests, and 10 times greater than Western private forests [2]. Timber industry, world leaders, non-governmental organizations, and non-industrial private forest landowners have acknowledged a synergistic relationship between economic goals and ecosystem services and have labeled it 'Climate Smart Forestry' (CSF).

CSF fundamentals emphasize enhanced forest carbon sinks; thus, forests are leveraged as a nature-based solution for climate change. In turn, forest carbon sinks can help nations meet emissions-related goals, such as the Paris Climate Agreement [3], and can help private landowners with environmental, social, and governance (ESG) benefits [4]. Fortunately, the scientific community has a firm understanding of forest carbon cycles [5], especially simple loblolly pine plantation carbon pools and fluxes [6], so it is well understood how to increase forest carbon capture. However, there are knowledge gaps in terms of CSF definition, the relationship between traditional silviculture and CSF silviculture, timber product carbon storage, and data collection for CSF—to mention only a few.

Southern commercial forestry is an attractive option for CSF. This is mainly due to the large amount of Southern pine research in the past 50 years which has led to enormous production gains (e.g., [7]). However, there is minimal North American-based scientific literature on CSF and no reviews focused on North American, or even Southern, CSF. To address the literature shortfall, in this paper, we aim to provide a comprehensive framework of Southern CSF through a literature review. At large, this review demonstrates that Southern working forests increase carbon storage through tree biomass and forest products. The review will help forest landowners, forest managers, and forest research professionals understand how traditional practices and product use have positioned the South well for CSF engagement. Additionally, this paper will identify key areas for further CSF research.

1.1. Guidelines

European forest researchers have dominated the CSF arena and we will use their work as guidelines. There have been European-wide meetings to discuss and analyze CSF indicators [8], frameworks developed for successful CSF, and perspectives on CSF remote sensing [9]. More importantly, there are efforts to understand European progress towards specific CSF goals and increase synergistic CSF outcomes with forestry best management practices [10]. Nabuurs et al. [10] indicated that CSF has three main objectives, likely borrowed from agricultural perspectives on climate change [11]. The objectives are:

(1) Reduce and remove greenhouse gas (GHG) emissions to mitigate climate change through forestry (i.e., increased forest carbon storage);
(2) (Adapt forest management to enhance the resilience of forests;
(3) Secure forest production and forest income sustainably.

In short, CSF is a synergistic blend of silviculture and climate change mitigation/adaptation. For plantations in the U.S. South, CSF can naturally leverage the compatibility of production forestry and climate change mitigation tactics to increase climate benefits realized from forest industry (Objective 1). We suggest that CSF is a general concept rather than a static silvicultural prescription (i.e., thinning, fertilization, etc.), as CSF is system specific, and Southern plantation CSF practices are likely not compatible in other U.S. regions. We do not suggest all U.S. forests should be managed as plantations; rather, we highlight how Southern pine plantations are useful in understanding CSF.

1.2. Current Status

Climate Smart Forestry has become a hot topic within the academic, investment, and political realms. The CSF trend has been reflected in increased mentions in peer-reviewed papers. A 2008 Google Scholar search for 'Climate Smart Forestry' literature yielded zero results (3 May 2022). The exact 2021 search yielded 3240 results (3 May 2022). Likely, this abrupt increase was supported by the foundation of past production-oriented forestry research. For example, one of the first mentions of 'climate smart' Southern forestry practices occurred in Vose and Klepzig [12], a book on how to apply traditional Southern silvicultural methods under novel climate change conditions.

Speaking to forest investments, since the 1980s, sawlog and pulpwood production has become a popular alternative asset class [13]. In recent years, conservation forestry investments (e.g., carbon markets) that place value in ecosystem services have optimized timberland investment portfolios as a strategy to increase risk-adjusted returns [13]. As such, there have been calls to increase timberland investment research to better understand the sustainability of ecosystem service evaluation alongside traditional timber-oriented goals [4].

In the political arena, United States Department of Agriculture (USDA) has funded CSF, the Executive branch has developed CSF policy, and forest certification programs have now incorporated CSF into the certification process. In early 2022, USDA announced a USD

1 billion program for 'Partnerships for Climate-Smart Commodities' [14]. A program staple is the development of scientifically rigorous methods to measure, track, and verify forest biomass carbon. Further, the Biden Administration in January 2021 (Exec. Order No. 14008, 2021 [15]) and April 2022 (Exec. Order No. 14072, 2022 [16]) signed executive orders to strengthen CSF policy. Executive Order No. 14008 supports climate-smart practices to produce verifiable carbon reductions via sustainable bioproducts and fuels, while Executive Order No. 14072 works to enlist climate smart conservation to use nature-based solutions for climate change. On a separate note, forest certification programs, such as the Sustainable Forest Initiative (SFI), now require CSF objectives to be met, primarily based on climate change mitigation and adaptation standards [17]. With academic, industry, and political support it is now upon forest managers, academics, and industry professionals to utilize the opportunity.

1.3. Research Origin

It is difficult to ascertain where CSF conceptually originated. In the published literature, the CSF term first appeared in Nitschke and Innes [18] in 2008, approximately at the same time 'Climate Smart Agriculture' was first articulated [11]. More useful CSF definitions and explicit CSF applications appeared in a 2015 European report authored by Nabuurs, et al. [19]. We argue that CSF foundations were built on previous climate change and plantation silviculture research that focused on climate change mitigation and adaptation. Since the 1980s, climate change adaptation and adaptation research on net primary production [20], radiative forcing [21], tree physiology [22], sustainable forest production [23], and timber supply and demand [24] initiated the CSF platform. Simultaneously, forest researchers focused on improved Southern pine plantation aboveground production [25]. Silviculturists developed specific research on site preparation [26,27], fertilizer use [28,29], and weed control [30]. Together, climate change and Southern silviculture research have likely acted synergistically—climate change researchers have identified environmental concerns and silviculturist have produced management solutions. In the current literature, the blend between the climate change and silviculture literature has developed topics such as increased forest carbon storage (mitigation) [31], product substitution (mitigation) [5], species replacement (adaptation) [32], or density management (adaptation) [33].

2. Aim

North American forestry academics have left CSF virtually untouched. The aim of this paper is increase CSF comprehension within the U.S., by highlighting loblolly pine, the presumably most productive and prolific species in the Southern U.S., if not the United States. We will clarify how past Southern forestry research fits into the emerging CSF field and provide opportunities for further investigation. To address the stated CSF objectives of (1) sustainable stand production, (2) CO_2 removal and storage, and (3) forest adaptation and resilience, we focus on the following topics: aboveground stand production, forest products, and data collection. Largely, we focus on mitigation rather than adaptation. Each topic section will provide details on CSF applications and avenues for further research. For this paper, the 'Southern United States' include the states of Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia, i.e., the major loblolly pine physiographic regions: Piedmont, Lower Coastal Plain, Upper Coastal Plain, and Gulf Region [25].

Panel 1: Quick reference for terms.

Biogenic carbon: Carbon derived from biomass

Fossil fuel carbon: Carbon derived from combustion of such fuel

Life cycle assessment (LCA): Evaluation of the inputs, outputs, and the potential environmental impacts of a product system

Carbon storage: For this paper, unless specified, aboveground tree or forest biomass

Embodied carbon: Greenhouse gas emissions (CO_2) associated with the manufacturing, transportation, installation, maintenance, and disposal of a product or building. Dependent on LCA system boundary.

3. Loblolly Pine Silviculture

3.1. Aboveground Stand Production

CSF Application: Aboveground tree carbon is the easiest for silviculturists to manipulate for mitigation purposes. There can be select adaptation benefits from increased aboveground carbon.

Southern pine plantation silviculture is truly a success story in terms of increased carbon storage. Pine plantations are now considered a large carbon sink at the stand [34] and landscape level [35] across the commercial range of loblolly pine. This was not always the case. In the 1950s, Southern pine plantations totaled forests less than 0.8 million hectares [36] with a net growing stock equal to 2900 $Tg_{aboveground}$ C. Now there are over 16 million hectares of planted Southern pine and a net growing stock of 5600 $Tg_{aboveground}$ C (+93%) [1].

Site carbon storage (stem productivity) has increased due to management options that have increased site quality such as improved genetics and silviculture [37,38]. Stem production is important because this is where the majority (~55%) of aboveground loblolly pine carbon is stored [6]. Silvicultural stem-production effects are often additive in nature [39,40], so we mention each silvicultural method separately. Selected studies are a fraction of Southern plantation silviculture literature and are also often representative of study-site ephaptic features.

3.2. Improved Genetics

CSF Application: Tree improvement has increased landscape-level carbon capture (mitigation) and increased forest resilience to potential abiotic and biotic threats (adaptation).

Planting genetically improved seedlings (1st and 2nd generation, half-sib) in the South has increased steadily since the 1960s [41]. Genetically improved seedlings are products of classical breeding techniques, not genetically modified organisms (GMOs), that have been selected for superior phenotypes based around stem volume, stem form, and fusiform rust (*Cronartium quercuum f.sp. fusiforme*) resistance [42]. As a result, stand volume production and stand carbon storage have increased. From 1968 to 2007, genetic improvement increased loblolly pine carbon storage by 13% (9865 Tg C), compared to non-improved loblolly pine carbon storage [8765 Tg C, 41]. Production gains are predicted to continue. Third-generation full-sib seedlings (+63% volume vs. non-improved) are now operational and 17% (136 million seedlings) of the 2018 planting season were full-sib seedlings [42]. Beyond production, genetic improvement has also benefited tree health. Improved seedlings have been linked to Southern pine Beetle (SPB, *Dentroctonus frontalis* Z.)-resistant trees [43]. Possible explanations for SPB resistance could be from increased resin flow [44], lower susceptibility to storm damage [40] from larger, deeper root systems [45], and lower fusiform rust incidence (healthier trees, [42]), potentially aided by genomic mapping efforts [46]. In-turn, improved stand health has increased carbon production via decreased mortality and increased tree vigor (i.e., [47]).

3.3. Site Preparation

CSF Application: Site preparation has increased seedling survival (adaptation) and stem productivity (mitigation).

Site preparation optimizes sunlight, nutrient, and water availability to shade-intolerant loblolly pine seedlings. This results in decreased interspecific competition and increased seedling survival [25]. In the Upper Coastal Plain and Piedmont, the practice has evolved from intensive mechanical practices, such as tillage and windrowing, to less-intensive chemical site preparation [27], due to decreased nutrient displacement [48]. Herbicide preparation treatments have increased (+10%, year six) seedling survival, compared to mechanical treatments such as burn-only and burn-chop treatments [49]. Operational chemical site preparation before planting (glyphosate, imazapyr, e.g., [50]), followed by burning increased volume production through year 21 in the Upper Coastal Plain and Piedmont [51,52]. Compared to a burn-only scenario, this translates to 56% (59.5 Mg C ha^{-1}) to 60% (61.1 Mg C ha^{-1}), dependent on application, more stem carbon storage at harvest (year 21, [49]). It should be noted, mechanical preparation (sub-soiling, bedding) is still used to create adequate bare mineral soil conditions on rocky sites (e.g., Upper Gulf Region, [53]) and increase soil drainage in excessively wet sites [54]. Additionally, herbicide-treated seedlings have greater vigor and resistance to pest-induced mortality such as pine tip moth (*Rhyacionia* spp.) [55].

3.4. Herbaceous Weed and Woody Control

CSF Application: Vegetation management can increase stem carbon storage via *decreased competition for soil nutrients and increased long-lived product (mitigation).*

Early (i.e., herbaceous weed control, 'HWC') and mid-rotation (i.e., 'woody release') vegetation management are two separate strategies commonly used to eliminate herbaceous and woody vegetation in favor of faster growing loblolly pine. HWC increases carbon gain early in rotation, compared to other treatments such as a woody release treatment or mid-rotation fertilization, which increases carbon later (Figure 1).

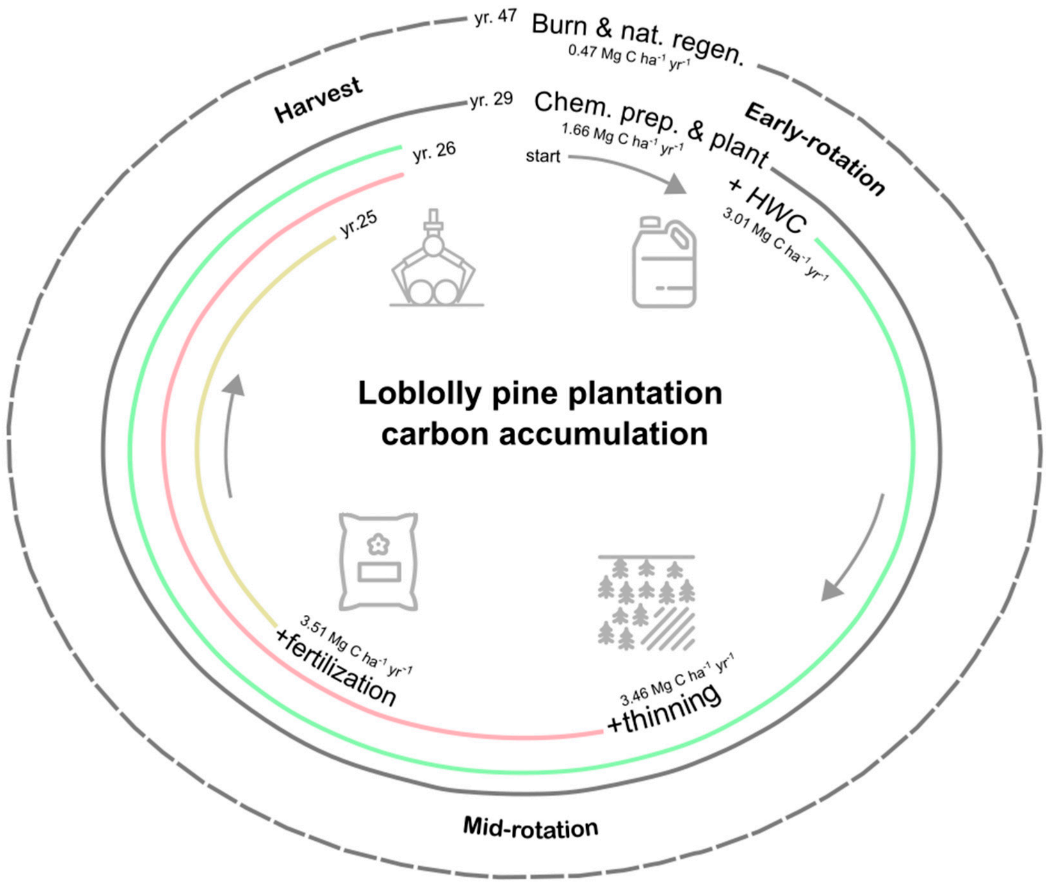

Figure 1. Loblolly pine plantation aboveground carbon accumulation rates with common operational silviculture, i.e., chemical prep and plant = chem. prep. and plant only; fertilization = chem. prep. and plant + herbaceous weed control (HWC) + thinning + fertilization. Number by treatment = average yield till harvest. Dashed circle = baseline. Arc terminus = rotation age. Data from Oneil [56], where harvest was determined at 6% return-on-investment, and the data represent Southern averages, not an existent stand.

One common strategy is imazapyr and/or glyphosate application after planting to control herbaceous weeds [57], along with sulfomethuron methyl and metsulfuron meythyl application to control early woody plant growth [58]. Later in rotation, if needed, the additional application of imazapyr and/or triclopyr can be used for woody release (not pictured in Figure 1) [59]. Competition control has increased stand-level stem carbon in various physiographic regions such as the Piedmont [60], Lower Coastal Plain [61], and the Florida Coastal Plain [62]. The magnitude of treatment response can be dependent on soil drainage and nutrient pools. On some Coastal Plain sites with poor drainage and low nutrient reserves, herbicide increased stem production by 70% (46 Mg C ha^{-1}) [37]. Well-drained Piedmont and Upper Coastal sites with higher nutrient reserves had slightly lower responses, +60% (63 Mg C ha^{-1}) [49]. Herbicide application also leads to greater sawtimber production [37], and the potential for more long-lived products (see 4.4). On a financial note, mid-rotation herbicide treatment (USD 153 ha^{-1}) has recently been more cost-effective than fertilization (USD 240 ha^{-1}) due to 1) decreased herbicide costs ($-$0.49% yr^{-1}) 2), increased fertilizer costs (+0.46% yr^{-1}), and current low sawtimber prices (~USD 25 ton^{-1}) [63].

3.5. Thinning

CSF Application: Density management results in increased residual stem production, carbon storage (mitigation), and greater resistance to abiotic and biotic events (adaptation).

Thinning is a tool to remove unwanted stems and increase the growth of residual stems. In mid-rotation loblolly pine plantations, 'thin-from-below' is common with canopy closure, i.e., when interspecific competition and density-dependent mortality rises. Decreased stand-density (thinning) results in lower stand-level aboveground biomass (carbon) [64]. Despite lower stand-biomass, thin-from-below is a production- and health-oriented strategy to ultimately increase sawtimber proportion [65]. For example, in the Lower Gulf Region, in year 7 and 14, below thinning increased the average tree diameter by 45% (21.8 cm thin, 15.0 cm non-thin) by age 17 [66]. Additionally, Hennessey, et al. [67] found that 21-year-old non-thinned stands had approximately six-times more mortality than thinned stands. Production-wise this equates to 33% of trees in non-thinned stands classified as sawtimber, whereas 92% of trees in thinned stands can be classified as sawtimber [67].

The future Southern landscape is predicted to have greater Southern pine Beetle infestation [68] and more severe wind events [69]. Thinning can limit stand susceptibility to such insect outbreaks and extreme weather events. Thinning has significantly decreased Southern pine beetle infestation severity [70], spread [70], and outbreak number [43]. Speaking to weather, mid-rotation thinning can mitigate steam breakage due to extreme winds [71], and in some cases, decrease mortality from ice-accumulation [72]. These few examples highlight the trend that stand density management is essential for mitigating events that can limit carbon accumulation.

3.6. Fertilization

CSF Application: Nutrient amendments lead to increased aboveground carbon storage (mitigation), shorter rotation age (adaptation), and increased long-lived product (mitigation).

Fertilization has increased carbon storage across precipitation and soil texture gradients in loblolly pine's commercial range [34,73,74]. Research has established a common mid-rotation prescription of 28 kg P ha^{-1} and 225 kg N ha^{-1} (e.g., [75]) to increase stem production and shorten rotation age (Figure 1). On average, nutrient amendments can increase volume production by 60% over eight years (+0.14 Mg C ha^{-1} yr^{-1}, [76]); when fertilization follows mid-rotation, the thinning effects on diameter growth are often synergistic [77]. From fertilization, net ecosystem carbon storage increased in stands located in the Upper Gulf (xeric, well-drained), Piedmont (mesic, well-drained), and Lower Coastal Plain (mesic, poorly drained) regions [34]. Additional nutrient availability can typically decrease rotation age [76] and increase sawtimber product proportion [78]. Such additional benefits have the ability to increase stand and wood product carbon over multiple rotations [79].

Fertilizer's contribution to GHG emissions is complicated since its impact is dependent on the product generated, e.g., pulpwood, sawtimber, or biomass [80]. Generally, sawtimber products can accumulate and offset carbon more effectively than pulpwood products [78,81]. Across 100-years, life-cycle-analysis (LCA) showed that sawtimber rotations with fertilization stored 135% (61 Mg C ha^{-1}) more carbon than pulpwood rotations with fertilization (26 Mg C ha^{-1}), due to a greater product lifespan, less product landfill accumulation, and increased product half-life [79]. In specific circumstances, fertilization can be justified on short, bioenergy-focused rotations (see Section 4.5). If emissions savings from increased bioenergy use and reduced coal use are greater than fertilization manufacturing, there will likely be net carbon savings [82,83]. This is especially true when pulpwood rotations, which lead to net GHG emissions, are compared to biomass rotations, which lead to net GHG reductions [80].

Despite predicted increased fertilizer use [75], fertilized forest area has decreased from 640 thousand ha in 1999 to 240 thousand ha in 2016 [84]. This has been attributed to low sawtimber prices in the late 2000s [84] and lower, nuanced fertilizer prescriptions [77]. As mentioned in 3.4, herbicide application is now more cost-effective.

Fertilizer application for increased stem carbon has compromises. There are environmental consequences from cradle-to-gate from fertilizer use such as increased global warming potential and eutrophication. Fertilized stands (site preparation, herbicide, thinning, plus fertilization) compared to non-fertilized (site preparation, herbicide, thinning only) can have 1331% (6.15×10^{-2} kg C ${m_{sawlog}}^{-3}$) more global warming potential and 1340% (8.30×10^{-4} kg N eq. ${m_{sawlog}}^{-3}$) more eutrophication potential [56]. Though the percent increases are drastic for global warming and eutrophication potential, absolute values are low on a per sawlog basis.

3.7. Harvest

CSF Application: Net carbon storage is achieved through silviculture, harvests, and replanting (mitigation).

When clear-cut harvests are followed by replanting, there is greater overall long-term carbon accumulation compared to no-harvest scenarios (Figure 2) [85].

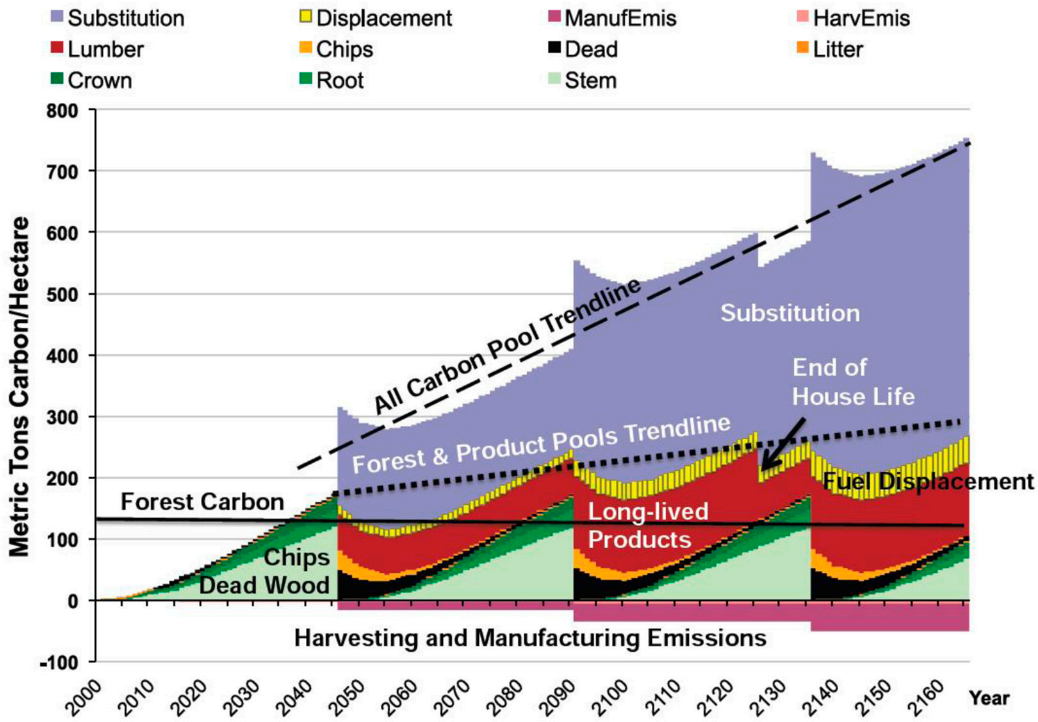

Figure 2. Carbon pools in forest stand, forest products, and under forest product substitution. From Maggard et al. [85]. Originally developed for sustainable forest management in the Pacific Northwest by Perez-Garcia et al. [86] and Lippke et al. [87].

On average, plantation silviculture can yield 2.72 Mg C_{sawlog} ha^{-1} yr^{-1} on a 30-year rotation [56]. This translates to 235 Mg C_{stem} needed to produce 139 Mg C_{lumber} or 1 m^3 of planed, dry lumber [88]. In the big-picture, 100-year models indicated four consecutive loblolly pine rotations stored 542 Mg C ha^{-1} between stand, wood product, and landfill pools [89]. When harvests do not occur, stands can be overstocked, experience decreased growth, have increased mortality, and have decreased carbon pools [85]. Compared to naturally regenerated loblolly pine stands, site preparation with planting can considerably decrease rotation age from 47 to 29 years and increase carbon storage rate from 0.47 Mg C ha^{-1} yr^{-1} to 1.66 Mg C ha^{-1} yr^{-1} (Figure 1). Further treatments of herbaceous weed control (HWC) + thinning + fertilization can raise carbon storage to 3.51 Mg C ha^{-1} yr^{-1} and shorten rotation age to about 25 years (Figure 1). Speaking to adaptation, production-minded silviculture may decrease the risk of natural disturbances (e.g., [90]) through shorter rotation ages.

Silvicultural activities emit carbon but only negate a small fraction of stored carbon in wood products (Figure 2). The most intensive plantation emission profile (i.e., HWC + thinning + fertilization) represents only 0.8% [56] of 255 kg C stored in 1 m^3 of dry, harvested sawlogs [91]. Not only are silvicultural-related emissions small compared to stored carbon, but silvicultural activities only represent 25% (0.7 kg C m^{-3} sawlog) of rotation-wide emissions. Gas and diesel consumption, from thinning and harvest, emits the most carbon in rotation (75%, 2.1 kg C m^{-3} sawlog) [56], also documented by others [92]. In terms of product type, commercial thinning (100% pulp) emits 88% more carbon (1.37 kg C m^{-3}) than final harvest (0.73 kg C m^{-3}), likely driven by greater fuel use (+8%) [56]. However, pulpwood is second to sawtimber volume (profit) in operational systems, mid-rotation thinning produces ~80% pulpwood, and final harvest produces ~15% pulpwood volume (Pers. Comm., The Westervelt Company, July 2022).

3.8. Future Research

If forests are to be used as a biological pump to store atmospheric carbon, additional research is needed to understand the potential tradeoffs enroute to increased forest carbon storage. Drier growing conditions in Western, xeric stands could be a roadblock. It has been documented that reduced soil moisture decreases volume growth [93] and photosynthesis [94]. Planting more drought tolerant shortleaf (*Pinus echinata* Mill.) or longleaf pine (*Pinus palustris* Mill.) seedlings could alleviate the drought roadblock and simultaneously provide greater biodiversity. However, increased biodiversity could change the economic objectives and trends in long-term carbon storage. We recommend forestry researchers and professionals refrain from 'carbon tunnel vision', and not pursue carbon gain at the expense of essential ecosystem services such as biodiversity.

Relationships between belowground carbon and aboveground carbon storage must be examined as well. Within loblolly pine's commercial range, an astonishing 2.6 Pg of topsoil carbon is stored and stabilized on 34.7 million acres [95]. This massive carbon pool is partly due to silvicultural interventions that have increased the site index (i.e., productivity, [96]). However, it is not well understood if silviculture (e.g., genetic improvement, fertilization) will sustain soil carbon storage trends under anticipated climate change events. In the end, belowground consequences of increased stem carbon storage must be understood to help forest managers sustainably maximize total stand carbon.

4. Timber Products

4.1. Carbon Reduction Pathways

Timber products can be leveraged to decrease atmospheric emissions (Figure 2, [86]). Compared to carbon accumulation in no-harvest scenarios, there can be greater net carbon storage when harvests occur and timber products are manufactured [85,97,98]. Product type is important to consider. As mentioned in 3.6 and 3.7, sawtimber products are more effective at reducing carbon emissions than pulpwood products due to longer product lifespan, lower biogenic carbon emissions, and greater potential fossil-fuel carbon displacement. Such discrepancy brings to light the different ways timber products decrease atmospheric CO_2. Some common pathways are storage, energy, and avoidance [97]. The storage pathway physically incorporates wood into products, so the wood does not rot, burn, and emit CO_2. The energy pathway displaces fossil fuel combustion with biomass combustion that results in lower net CO_2 emissions. The avoidance pathway substitutes wood products for carbon-intensive products such as steel and concrete, where less fossil fuel carbon is emitted. Timber products typically utilize a combination of storage, energy, and avoidance pathways [97].

4.2. Avoidance Pathway

The avoidance pathway could be the most promising pathway due to the enormous carbon footprint of raw material procurement. Globally, material production is a substantial source of CO_2 that has trended upwards. From 1995 to 2015, global material production rose 120% from 1.4 Gt C yr^{-1} to 3.0 Gt C yr^{-1} [99]. In 2015 terms, material production represented a *quarter* of global CO_2 emissions [99]. Key contributors to emissions were iron and steel (31%, 0.9 Gt C yr^{-1}), along with cement, lime, and plaster (24%, 0.7 Gt yr^{-1}) [99]. Clearly, simple steel, iron, and cement manufacture avoidance will result in carbon savings. This can be achieved under an increased timber-product use scenario, where the avoidance pathway controls carbon savings with storage and energy as minor carbon-saving pathways [97].

Compared to iron, steel, and cement production, wood production can be considered carbon neutral. This is first supported by wood product carbon storage throughout the manufacturing process (Figure 3) and product lifespan (Figure 2).

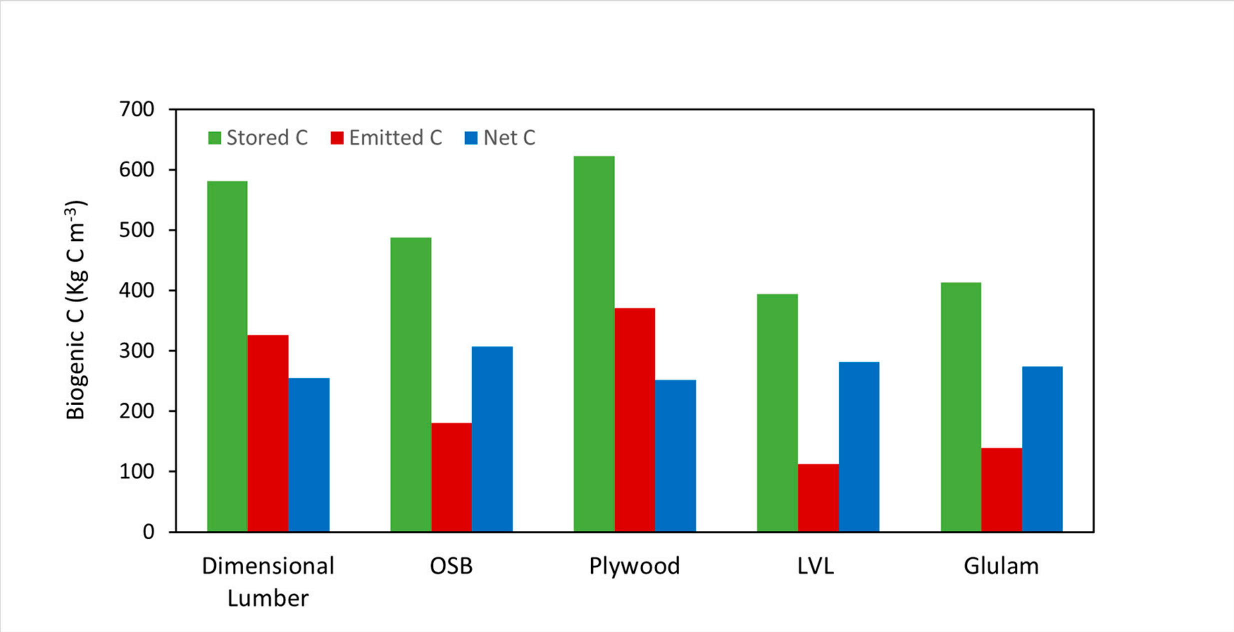

Figure 3. Biogenic carbon (temporary storage) for Southern-sourced wood products from raw material extraction through product installation. OSB = oriented strand board; LVL = laminated veneer lumber; Glulam = glue laminated lumber. Data from CORRIM Library of LCAs on Wood Products (https://corrim.org/lcas-on-wood-products-library (accessed on 19 July 2022) [100]).

Second, greater global wood production will lead to global change in supply and demand, complemented by managed forest expansion, and greater net carbon storage [101–103]. Wood products are carbon neutral because wood carbon is eventually emitted back to the atmosphere at end-of-product-life (Figure 2, end-of-house-life). For Southern pine, that means the previously mentioned 255 kg C per 1 m^3 of dry lumber (Section 3.7) is a temporary biogenic carbon pool [91]. Wood carbon neutrality is supported by a constant, if not increased, forest carbon storage trend in the U.S. since 1990 [104]. Fortunately, wood carbon release is slow if the wood product has a long lifespan [105,106]. Wood product carbon neutrality could give importance to displaced fossil fuel carbon, which could result in substantial long-term reductions in atmospheric carbon [85].

4.3. Substitution

Substitution is the amount of carbon emissions foregone from wood utilization replacing more carbon-intensive practices (Figure 2). Typically, substitution is mainly achieved via the avoidance pathway [97]. Substitution is dimensionless, as it can be presented as units of 'fossil-fuel carbon' foregone per unit of 'wood carbon' (e.g., kg kg^{-1}). Generally, values greater than 0 represent carbon reduction, while values less than 0 represent greater fossil fuel carbon emissions. Values are case-specific, but meta-analyses have shown, globally, that substitution factors can often be less than 1 [107] or just slightly above 1 [108]. For example, Southern-based wood products in non-residential construction can have a substitution factor of 2.83, while similar products sourced from the Western United States have a factor of 0.60 [109]. This is because growth rate is one of the essential determinants for effective wood product substitution [110]. As noted previously on the positive relationship between silviculture and biogenic carbon storage, production-oriented silviculture can also help to increase substitution factors.

4.4. Sawtimber Utilization

CSF Application: Sawtimber products can lead to carbon savings beyond the stand (mitigation).

Commercial forestry stores biogenic carbon through long-lived, sawtimber products (storage pathway) and avoids fossil fuel carbon emissions via displacement (avoidance pathway) [106,111]. Compared to pulpwood products (see Section 4.5), sawtimber products have a longer lifespan (75 to 100 years [112]), a longer half-life (30 to 80 years [113]) and represent more products (carbon) in-use (40%) and in landfills (40% [113]). Under cradle-to-installation analysis, Southeastern sawtimber products such as dimensional lumber, oriented strand board (OSB), plywood, laminated veneer lumber, glulam, and cross-laminated timber have led to substantial net-positive biogenic carbon storage (Figure 1). Net-carbon storage at the product level can be scaled up to net-carbon storage in residential [112] and commercial [114] construction. In Atlanta, GA, USA, if residential construction wood use is increased by 2%, fossil fuel carbon emissions could decrease by around 50%—a substitution factor of 2.8 [112]. Similarly, Southeastern commercial mass-timber buildings built with glue laminated lumber (glulam) and cross laminated timber (CLT) can result in 40% less embodied carbon than traditional concrete buildings [114], due to less fossil fuel carbon emitted during manufacturing [115].

Increased building wood-use can ultimately lead to more favorable landscape-level carbon balances. The Southern region has the greatest potential to do so through housing starts. Currently, the South represents around 50% (~450 thousand yr^{-1}) of housing starts in the U.S. (Northeast ~60, Midwest ~125, West ~200 thousand yr^{-1}) [116]. Southern housing-start dominance has been predicted to remain until at least 2070, with the region responsible for, on average, 10 million Mg C yr^{-1} (50% nationwide housing C storage yr^{-1}) in the form of single- and multi-family housing [116]. Increased wood use could even raise average housing carbon storage. For instance, high wood-use models have predicted Southern pine plantations could increase in area, leading to increased carbon storage (+80% compared to baseline) via increased construction demand [109]. Despite predicted benefits, construction wood substitution is system specific and can vary from −2.3 to 15 [117].

Wood utilization in buildings can be the lynchpin to global tree planting initiatives targeted at enhanced carbon storage [85]. This is because plantation forests can surpass mature forests carbon storage after multiple rotations [109]. Harvested and replanted forests represent continued carbon reductions [85], and result in a forest carbon equilibrium [118]. Lippke et al. [85] asserted that demolished steel and concrete structures cannot recover used energy (carbon), but wood-based buildings can with each sequential wood-based building replacing a traditional steel and concrete building. A 100-year projection agreed, loblolly pine rotations harvested for CLT-based buildings resulted in +200 Mg C ha^{-1} to +350 Mg C ha^{-1} [105]. To obtain the maximum (350 Mg C ha^{-1}) carbon storage regime, storage in buildings must be first initiated by, at least, operational silviculture (Figure 1) [105]. This indicates that active management such as fertilization, vegetation control, and genetic deployment are the primary foundations to increase carbon storage, in agreement with others [38,96].

Sawtimber utilization has tradeoffs. Increased wood production could cause decreased forest inventory due to increased wood product demand. It has been predicted that forest inventory could decrease in the short- to mid-term (>50 years [101,109]). However, in the long-term (100-plus years), forest inventory could recuperate due to increased leaf gas exchange (i.e., CO_2 fertilization [34]) and increased forest investment (i.e., planting, [101]). On another note, mid-term forest inventory reduction will likely affect biodiversity. Expanded wood utilization and maximum carbon storage may not be compatible with biodiversity integrity in all forested systems [119]; therefore, they should only be focused on when it is ecologically prudent.

4.5. Pulp and Paper Product Utilization

CSF Application: Pulp and paper products are vastly different than sawtimber products. Additional research is needed to understand how pulp and paper could increase carbon storage (mitigation).

Globally, the pulp and paper industry generates almost 2% of annual GHG emissions [120]. Vast industry emissions can translate to product-level emissions, such as in freesheet and mechanical paper [106]. Despite large- and small-scale carbon emissions, there are few peer-reviewed LCAs on specific Southern products such as paperboard, tissue, and market pulp. This makes direct comparisons to Southern sawtimber products problematic. Nevertheless, there are major takeaways on pulp and paper carbon. Compared to sawtimber products, pulp products have a shorter lifespan (0.5 to 50 years [121]), a shorter half-life (8 to 15 years [113]) and represent a smaller carbon proportion of products in use (4%) and in landfills (16%) [113]. In reference to United States trends, tissue and towel products consume the largest amount of embodied carbon (469 kg C $Mg_{product}{}^{-1}$) and market pulp consumes the largest amount of biogenic carbon (614 kg C $Mg_{product}{}^{-1}$) [122]. Unbleached paperboard (i.e., cardboard) dominates overall annual production (22.5 $Tg_{product}$ yr^{-1} [122]); thus, its production emits the most carbon per year.

Embodied carbon evaluations across pulp and paper products are complex for a few reasons. First, many pulp and paper products require specific mills, raw materials, technologies, chemicals, and energy inputs [123]. For example, unbleached paperboard produces 241% less embodied carbon (195 kg C $Mg_{product}{}^{-1}$) than sanitary tissue, but unbleached paperboard also produces 440% more biogenic carbon (1515 kg C $Mg_{product}{}^{-1}$) [122]. Greater biogenic carbon from paperboard production is likely due to on-site bioenergy combustion, sourced from mill pulping liquor and waste wood [122]. This brings to light different carbon-release timescales and subsequent challenges with LCA comparison. Second, pulp and paper products vary in lifespan. Sanitary tissue has a very short lifespan, 0.5 to 1.5 years, cardboard slightly longer, 2 to 8 years, and book lifespan is substantially greater, 10 to 50 years [121]. However, sawtimber product lifespans are more congruent because lifespan is assumed equal to building-life [113]. Lastly, and maybe the most problematic, pulp peer-reviewed LCA methodologies vary. In particular, there have been many induvial LCA articles (e.g., [122,124,125]), with a wide range in functional units, from a 'paper towel roll' [125] to $Mg_{product}$ [122], and a wide range in scope, from nation-wide carbon estimates [126] to specific pulp operations [127].

Despite carbon comparison issues, there is still potential for the pulp and paper industry to realize carbon savings in the avoidance pathway from onsite carbon capture, product recycling, or substitution. Speaking to carbon capture, the United States pulp and paper industry heavily relies on pulping liquor and biomass (~77% of fuel) for power [128]. Therefore, some have outlined how the industry could pragmatically capture and store biogenic carbon from plant boilers [128] to improve decarbonization efforts [123]. Thinking about recycling, pulp and paper products are more likely to be recycled than sawtimber-sourced products [113]. Instead of a biogenic-carbon focus, future research could focus on the embodied carbon impact of reduced virgin fiber use and increased material reuse efficiency [129]. Encouragingly, cellulosic fiber-based packaging has gained momentum to replace plastic packaging [130] and fiber packaging LCAs have shown carbon savings compared to plastic packaging [131]. Pulp and paper substitution benefits can subsequently be realized due to heightened renewability, recyclability, and enhanced biodegradable properties [132], a trend supported in long-term analysis [133]. Other metrics, such as water footprint accounting, have also been suggested to support freshwater ecosystem services in the sector [134].

4.6. Bioenergy Utilization

CSF Application: Bioenergy has capacity to lower CO_2 emissions in the long-term (mitigation).

The South can utilize enormous stand productivity to displace coal-fired power plants with biomass combustion [82,135]. In an analysis of Georgia's bioenergy potential, pulpwood and logging residue for bioenergy was predicted to save 222 million tons of carbon emissions over 50 years when compared to a 100% coal baseline [82]. However, bioenergy carbon accounting is complex. Different analyses can suggest net reductions or net emissions. Why the discrepancy? As with all analyses, different assumptions can alter predictions. The main issue is analysis scale. At the landscape level, energy generation from loblolly pine biomass, in place of coal-fired power plants, can lead to a net carbon reduction [82,135,136]—especially with whole trees or additional slash harvests [83,135]. At the stand level, the opposite has been found: wood-for-coal in the Southeast could result in net carbon emissions [137].

Harvest can be an underlying mechanism to create different outcomes between landscape- and stand-level investigations. At large spatial scales, increased harvest rates or disturbances have little effect on carbon storage. Often, as one stand is harvested or disturbed, another accumulates biomass; hence, the average carbon storage across many stands does not change dramatically [31]. At fine spatial scales (stand level), this is not true. Increased harvest rates will abruptly decrease and increase carbon storage in a traditional, cyclic pattern (e.g., crown, root, and stem carbon in Figure 2, [31]). For example, landscape-level silvicultural actions such as replanting [118,138] or managed forest expansion [101,139] will often produce favorable carbon balances [82].

Another issue is different temporal perspectives related to 'carbon debt' [135,140]. Generally, it is accepted that wood bioenergy utilization temporarily increases CO_2 emissions in the short term [135,141], but decreases CO_2 emissions in the long term, i.e., >20 years [138,141,142]. This is because of carbon debt from biomass combustion that must be 'paid back' via stem growth or replanting before carbon reductions are realized [141]. Carbon debt is extremely system specific. With tremendous loblolly pine aboveground productivity, payback time can only be one to three years [135,136], compared to 50 years in slower growing Southern hardwood systems [140].

4.7. Further Rersearch

As evidenced in Section 4.5, Southern pulp and paper product LCAs must be improved to determine precise carbon footprints. Additionally, substitution factors must be enhanced to reflect options related to end-of-product-life such as product reuse, incineration, or disposal in landfills (e.g., [143]). Some have shown that substitution can be overestimated [144] or altogether ineffective [145]. Overestimation can arise due to the static nature of substitution analyses and ill-defined system boundaries [107]. Thankfully, Hurmekoski et al. [107] suggested areas for substitution improvement and Howard et al. [146] highlighted common substitution assumptions. Ineffective substitution is a valid point; the argument contends that increased harvests could increase short-term carbon emissions [147]. In response to ineffective substitution perspectives, some have suggested that concentration on short-term emission reduction could lead to the failure of long-term emission reduction [148]. We echo calls for additional viewpoints on short- and long-term carbon reduction suitability [148].

Within the U. S., the Southeast may have the most flexibility to increase carbon storage potential. In the commercially dominated Southeastern U.S., there is substantially more carbon storage on private lands than other regions such as the Pacific Northwest or Northeast [149]. To harness this flexibility, we encourage more landscape-level analyses to include forest carbon and market responses (see [103]) to improve transparency on how demand and forest growth could be synergistic. For instance, increased timber product demand could be leveraged to encourage integrity of essential ecosystem services beyond the carbon cycle.

5. Data Collection

CSF Application: 'You can't increase what you can't measure' (mitigation).

We will briefly mention the power behind data-driven CSF. In situ and remote sensing are the two main categories of CSF-related data collection. We will focus on remote sensing that may be used to improve productivity estimation, such as the application of data acquired from new and ongoing satellite missions (e.g., Sentinel-2 imagery, Global Ecosystem Dynamics Investigation or GEDI, and the Ice, Cloud and land Elevation Satellite-2 (ICESat-2)) [150], or fine-scale observations collected from unmanned aerial vehicles (i.e., UAVs) [9].

In order to increase carbon storage in the South, carbon needs to be measured precisely, while also being affordable—not a new concern [5]. Ground-based tree survey data are precise but can be expensive and time-consumptive. Lidar-based estimates of traditional forest attributes (e.g., height, volume, basal area, aboveground biomass) can increase the precision of forest carbon measurements and enhance the estimation of other forest structural metrics such as height complexity and canopy cover [150]. One of the most appealing CSF applications of lidar-based estimations is to monitor and calculate forest carbon stock after harvest or other disturbances. At a landscape scale, Fagan et al. [151] showed how lidar can be combined with imagery to quantify Southern pine plantation expansion. The authors found that from 1992 to 2011, southern pine expanded into non-forest areas throughout the South by 1.08% yr^{-1} [151]. Using similar methods, Garcia et al. [152] determined pre- and post-fire forest carbon, or carbon release from fire. Here, the authors documented how the 2013 California Rim fire released 3 Tg C, similar to emissions from over 2 million cars yr^{-1} [152]. Comparable lidar applications could be employed to add clarity to CSF's impact on short- and long-term carbon storage in the South, such as outcomes from increased planting or increased harvest rates.

More precise estimations can benefit carbon accounting too. It has been indicated that California's Cap-and-Trade program has over-credited 30 million tCO_2e, worth around USD 410 million, due to coarse regionwide estimates [153]. Such blunders are troublesome and highlight an extensive need for greater scientific rigor in the carbon accounting sector [154]. Carbon credit platforms are not limited to the California system, as private platforms such as NCX or Core Carbon now offer carbon programs to Southern timberland owners. Improved estimation techniques will help the South capitalize on carbon markets honestly and continue efforts to combat climate change.

6. Conclusions

Southern CSF serves as part of the solution to combat climate change. We highlighted traditional silvicultural practices that increase stem productivity and concurrently store additional carbon. After harvest, forest products can be substituted for carbon-intensive products to help reduce carbon emissions (fossil fuel use) beyond the stand. The cooperative relationship between commercial forestry and carbon abatement highlights the pivotal role management plays in atmospheric carbon reduction. We contend, along with others [110,155], that non-management is not the most effective strategy to store additional carbon to combat rising atmospheric carbon. To advocate for increased CSF-centered management in all forest types, we call for (1) increased understanding on ecosystem service tradeoffs from carbon storage prioritization in forested systems; (2) CSF that promotes a cohort of ecosystem services, not just carbon storage; (3) substitution methodology standardization to help claim legitimate carbon benefits; and (4) increased remote sensing capabilities to increase measurement precision based around carbon accounting. Our review supports pragmatic climate change solutions sourced from traditional, production-oriented forestry practices with the help of carbon-conscious mitigation and adaptation objectives.

Author Contributions: Conceptualization, N.T.S., L.N., Y.P. and A.M.; Investigation, N.T.S.; Writing—Original Draft Preparation, N.T.S.; Writing—Review and Editing, L.N., Y.P. and A.M.; Visualization, N.T.S. All authors have read and agreed to the published version of the manuscript.

Funding: Partial funding support from The Westervelt Company, Resource Management Services, and Forest Investment Associates is greatly appreciated.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This manuscript was developed with help from Jonathan Lowery, Victoria Lockhart, Kirstie White, and MaryKate Bullen.

Conflicts of Interest: The authors declare no conflict of interest.

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