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Review

Opportunities for Research on Carbon Management in Longleaf Pine Ecosystems

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Abstract: Longleaf pine (*Pinus palustris* Mill.) savannas and woodlands are known for providing numerous ecosystem services such as promoting biodiversity, reducing risk of wildfire and insect outbreaks, and increasing water yields. In these open pine systems, there is also interest in managing carbon (C) in ways that do not diminish other ecosystem services. Additionally, there may be management strategies for accomplishing these same objectives in plantations and degraded stands that developed from natural regeneration. For example, C accumulation in live trees and C storage in harvested wood products could be increased by extending rotations and converting plantations to multi-aged stands. Belowground C storage could be enhanced by incorporating pyrogenic C into the mineral soil before planting longleaf pines in clearcut areas, but this may be contrary to findings that indicate that minimizing soil disturbance is important for long-term soil C storage. We suggest examining approaches to reduce total ecosystem C emissions that include using targeted browsing or grazing with domesticated livestock to supplement prescribed burning, thereby reducing C emissions from burning. The mastication of woody vegetation followed by a program of frequent prescribed burning could be used to reduce the risk of substantial C emissions from wildfires and to restore function to savannas and woodlands with hardwood encroachment and altered fire regimes. Many of these approaches need to be validated with field studies or model simulations. There is also a need to improve the estimates of dead wood C stocks and C storage in harvested wood products. Finally, eddy covariance techniques have improved our understanding of how disturbances influence longleaf pine C dynamics over multiple time scales. However, there is a need to determine the degree to which different silvicultural approaches, especially those for adapting ecosystems to climate change, influence C accumulation. Overall, our review suggests that there are numerous opportunities for research on C dynamics in longleaf pine ecosystems, and these systems are likely well-positioned to accomplish C objectives while offering other ecosystem services.

Keywords: carbon sequestration; carbon accumulation; climate change; ecosystem services; carbon markets

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1. Introduction

In the southern USA, forest landowners have shown increased interest in selling carbon (C) offsets to companies or regulated entities to derive an alternative or additional revenue source from their land. Longleaf pine (*Pinus palustris* Mill.) ecosystems could be an important contributor to "high-quality" or "charismatic" C offset programs, which not only reduce C emissions but also have significant social and environmental benefits. Longleaf pine ecosystems are well-positioned for high-quality C offsets because they feature long-lived trees that store C for long periods of time and are often managed for multiple ecosystem services [1]. Longleaf pine savannas and woodlands are also maintained and managed with frequent low-intensity prescribed fire. This reduces the risk of catastrophic wildfires and insect outbreaks (which release massive amounts of C) while increasing water yields. Longleaf pine savannas and woodlands are highly valued for their intrinsic biological diversity including numerous species of flora and fauna of conservation concern. Despite emerging opportunities for high-quality C offsets, there remains a poor understanding of how longleaf pine ecosystems can be managed to enhance C storage and sequestration while maintaining the diverse benefits these unique open pine systems provide. Thus, there is an urgent need to address the research gaps and identify management approaches that balance important ecosystem services with C offset programs. An important first step toward meeting this need is to accurately quantify and predict C stocks in longleaf pine ecosystems and harvested wood products.

Longleaf pine is found in widely distributed and fragmented naturally regenerated stands and plantations across the southern USA. Data, derived from inventories of trees on USDA Forest Service Forest Inventory and Analysis (FIA) plots and determinations of the forest type made by FIA field crews through 2023, indicates that longleaf pine and longleaf pine/oak (*Quercus* spp.) forests occupy about 2.29 million ha [2]. About 62% of this total area is in naturally regenerated stands. Naturally regenerated longleaf stands managed with frequent prescribed fire typically have low basal areas, sparse midstories, and diverse herbaceous ground cover [3]. These stand conditions also support many species of conservation concern, such as the gopher tortoise (*Gopherus polyphemus*) and red-cockaded woodpecker (*Leuconotopicus borealis*) [4], in addition to a highly diverse pyrogenic ground flora [5]. For wet–mesic longleaf pine sites maintained with prescribed fire, the mean species richness at the scale of 3 m^2 quadrats was 36 plant species, which was more than double that of xeric sites [6]. Another characteristic of low-density stands is that they have fewer evaporative losses than high-density stands, which can increase streamflow, extend the wetland hydroperiod, and promote groundwater recharge [7,8]. These co-benefits highlight the need to conserve the remaining tracts of naturally regenerated longleaf pine stands. Payments for enrollment in C offset projects could be a way to encourage landowners to retain and continue managing these stands instead of considering other forms of forest management or conversion to other land uses.

There may also be opportunities for improving the balance among C sequestration and other ecosystem objectives on degraded lands and in pine plantations. Some naturally regenerated stands of longleaf pine are in degraded states because fire suppression has led to the encroachment of mesic hardwoods and pines that are less fire-tolerant [3,9,10]. While these stands contain more C in competing woody vegetation, they have a higher risk of catastrophic wildfire than naturally regenerated longleaf pine stands managed with prescribed fire. Researchers used forest landscape models to compare C outcomes among prescribed fire exclusion, prescribed fire, and wildfire scenarios [11,12]. These studies indicated that prescribed fire scenarios resulted in lower C emissions and greater aboveground biomass over time compared to wildfire scenarios. A future research priority is to determine forest management approaches that balance the ecosystem benefits gained by using prescribed fire with enhanced C sequestration.

Monetary incentives for C management could help restore structure and function to degraded longleaf pine stands and provide an incentive for landowners to facilitate the conversion of longleaf pine plantations to a more representative open, structurally heterogenous, species-rich savanna or woodland condition. This could lead to better C outcomes than clearcutting plantations for pulpwood and small-diameter sawlogs or converting plantations to other land uses (e.g., row crop agriculture) by retaining larger trees and diverse age classes. Eddy covariance studies clearly established [13–15] that recently clearcut pine plantations are significant C sources to the atmosphere, since soil disturbance and exposure of the land surface to sunlight create ideal conditions for heterotrophic decomposition of woody debris and soil organic C pools [16]. While these ecosystem C fluxes are traditionally ignored in C offset projects, which focus on aboveground biomass accumulation, recent proposals emphasize the importance of monitoring such fluxes to maximize atmospheric C sequestration [17,18]. Overall, the conservation of stands with a structure and function that are in alignment with C and other ecosystem objectives is crucial. Just as important is identifying opportunities to enhance ecosystem services on marginal agricultural lands, degraded naturally regenerated stands, and plantations with poor stocking due to disturbances.

The main objective of this review article is to provide an overview of C stocks and accumulation in longleaf pine ecosystems by aboveground, belowground, and combined pools and longleaf pine C storage in harvested wood products. We also suggest potential strategies for enhancing C stocks and accumulation in both naturally regenerated longleaf pine stands and plantations. We acknowledge that some of these strategies may be cost-prohibitive for some landowners and that landowners may prefer to use other major commercial southern pine species because of their faster initial growth rates on some sites. However, as improved longleaf pine stock becomes more widely available and is, thus, available for planting considerations on sites with poor to intermediate site qualities, longleaf pine may be a good choice [19]. Finally, we identify important research needs and knowledge gaps (Figure 1), especially with regards to accurately quantifying C stocks and modeling C dynamics in longleaf pine ecosystems.

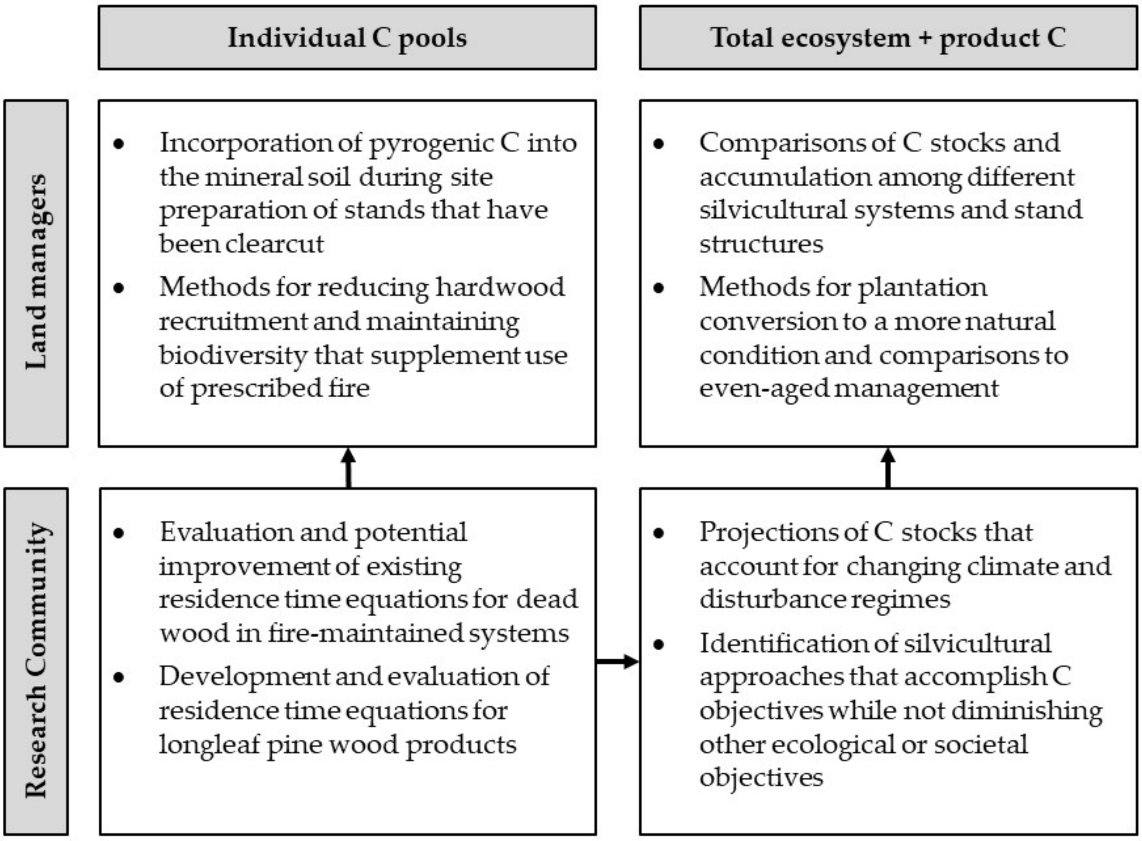

Figure 1. Examples of research priorities for longleaf pine ecosystems by individual C pools (e.g., mineral soil) and total ecosystem plus harvested wood product C and a land manager and research community focus. Arrows indicate that improvements in one research area could translate to better predictions and methodologies in other areas.

2. Aboveground C Stocks and Accumulation

Most evaluations of C accumulation in longleaf pine ecosystems utilize a chronosequence approach. These studies show that older stands have greater aboveground C stocks than younger stands, while C accumulates rapidly in the live trees of young stands [20,21]. The youngest stands in these studies were longleaf pine plantations, and most of the oldest stands were primarily derived from longleaf pine natural regeneration. Aboveground live tree C ranged from <1–74 Mg ha^{-1} and represented <1%–39% of the ecosystem C [21]. Maximum downed dead wood was <1 Mg ha^{-1}, and, with the exception of a 118-year-old stand, the standing dead wood C was <2 Mg ha^{-1}. While these results provide valuable insights into C accumulation as stands age, C stocks of longleaf pine plantations may be quite variable because of past land use, site preparation treatments, the type and quality of planting stock, and intermediate silvicultural treatments [22]. In naturally regenerated stands of other forest types, the species composition and age distribution of the trees within stands influence C stocks and accumulation [23]. Comparisons of C stocks and accumulation among (1) even-aged, mixed-species stands; (2) pure and mixed-species multi-aged stands; and (3) even-aged stands of longleaf pine could indicate which age structure and species composition best accomplish C objectives. In longleaf pine ecosystems, more research on quantifying C stocks and accumulation among stands where different silvicultural treatments have been implemented is also needed to inform decisions about approaches for accomplishing C objectives.

Additional research is also needed on the quantification of and methods for deriving longleaf pine dead wood C stocks. In the chronosequence study by Samuelson et al. [21], standing and downed dead wood C was unrelated to stand age. The authors hypothesized that dead wood C stocks were not significantly related to stand age because of the frequent use of prescribed fire in the stands of the study. Ulyshen et al. [24] also suggested that the low basal areas associated with some longleaf pine forests, subtropical climatic conditions, and abundant termite populations could limit downed coarse woody debris volumes. Further, coarse woody fuels in unburned, hurricane-impacted stands were shown to remain higher for 24 years following Hurricane Hugo than unimpacted or impacted and burned stands [25]. Future studies that quantify dead wood C stocks in longleaf pine ecosystems after disturbance events such as hurricanes would be useful for modeling C inputs to dead wood pools and for evaluating risk of high-intensity wildfires or insect outbreaks. Additionally, an evaluation of and potential improvements to existing residence time equations for dead wood in longleaf pine ecosystems [26], especially in ecosystems with low-intensity frequent fire regimes, would be useful for projecting dead wood C stocks over time.

Comparing projected forest C stocks and accumulation among different forest management strategies can be useful when long-term forest inventory data are not available. Gonzalez-Benecke et al. [27] used growth and yield projections and allometric equations to estimate aboveground C stocks over time for longleaf pine plantations with different thinning regimes. Site quality and rotation length were the major controls on projected C stocks. Another simulation study, indicated that longleaf pine plantations managed on rotations for sawlog production had greater aboveground C stocks over time than low-density, naturally regenerated stands managed with single-tree selection cutting [28]. Future research comparing projected C accumulation among even- and multi-aged silvicultural approaches, while concomitantly accounting for changing disturbance regimes [29,30], would also be useful for informing management and policy decisions related to C storage in longleaf pine ecosystems.

2.1. Extended Rotations

Across its native range, thousands of hectares of longleaf pine were planted on marginal agricultural lands during the late 1990s and early 2000s [31]. Plantations were established with Conservation Reserve Program (CRP) funds to limit the over-production of certain agricultural crops and to reduce soil erosion and improve water quality. One strategy for managing these stands to accomplish C objectives would be to adapt thinning schedules to focus on producing products from sawlog-sized trees. In longleaf pine ecosystems, products derived from sawlog-sized trees (e.g., poles, flooring, and structural timbers) have long residence times [19,32]. Managing stands for such products would require extending rotations longer than those typical for pulpwood production only. We acknowledge that some landowners are already managing longleaf pine plantations for sawtimber. Besides extending rotations, plantations could also be gradually converted to a more natural condition with new cohorts of longleaf pine developing from natural regeneration. This strategy would be congruent with objectives that include maintaining continuous forest cover and promoting multiple age classes within stands. Future research is needed to compare the C accumulation of plantations that are cut and replanted at the end of sawlog rotations with the C accumulation of plantations that are converted to a more natural condition.

2.2. *Reduced Risk of C Emissions*

Forest management practices that reduce the risk of C emissions from stand-replacing wildfires, insect and disease outbreaks, major wind and flooding events, or a combination thereof could be implemented at the landscape scale. For example, identifying site conditions that make trees more susceptible to windthrow during hurricanes could inform plantation management decisions about species selection and planting configurations and aid efforts to locate areas of tree mortality following storms [33]. Such efforts are often necessary to reduce fuel loads and the risk of high-intensity wildfires. Reducing the risk of C emissions could also be accomplished by adapting forests to the anticipated changes in insect and disease populations by managing tree densities and species composition [34]. This includes reducing the hazard and risk of insect and disease outbreaks and wildfire in fire-suppressed, overstocked stands with dense midstories. Restoration treatments that involve prescribed burning and hardwood removal may initially reduce live tree and soil C [35] but may limit the probability of substantial C emissions from catastrophic wildfires and insect and disease outbreaks. For example, mastication (also referred to as mulching) can also be used to reduce hardwood encroachment and to create favorable conditions for using prescribed fire (e.g., reduced midstories and ladder fuels). Future research opportunities include comparing the total emissions from initial mastication efforts and repeated prescribed fire with the emissions from catastrophic wildfire events.

2.3. *Wildlife Management*

Wildlife populations and predator–prey dynamics influence forest vegetation with implications for forest C stocks and accumulation. In longleaf pine ecosystems, predation by coyotes on white-tailed deer (*Odocoileus virginianus*) may influence forest C dynamics by altering the type of vegetation that white-tailed deer consume. For example, Cherry et al. [36] found that reduced predation risk resulted in an increase in oak recruitment to midstory canopy positions because white-tailed deer shifted their foraging preference from oaks to herbaceous groundcover. However, white-tailed deer's foraging on oaks may remain constant or increase given the increasing number of coyotes in many longleaf pine ecosystems. These interactions may be especially important to address in the context of C accumulation. Future research on the influence of ground-burrowing keystone species, such as the gopher tortoise and southeastern pocket gopher (*Geomys pinetis*), whose activities could lead to the redistribution of C among aboveground and belowground pools, is needed. The total number of herbivore species and their abundance is also likely to influence nutrient cycling and vegetation structure and composition. Enhancing our knowledge in these areas will improve our understanding of C dynamics in these ecosystems and potentially lead to recommendations on how wildlife populations can be managed to enhance aboveground and ecosystem C accumulation.

3. Belowground C Stocks and Accumulation

Soils represent a sizable portion of the total ecosystem C in longleaf pine ecosystems. For example, fine fraction (<2 mm) soil C to a depth of 1 m accounted for 39%–92% of the total ecosystem C in planted and naturally regenerated stands ranging from 5 to 118 years across the southeastern USA [21]. In these same stands, live root C accounted for 4%–22% of the ecosystem C. Additionally, longleaf pine tap roots extended to depths of 4 m, and the mean ratio of tap root mass to aboveground mass of trees selected for destructive sampling was 0.26. In naturally regenerated longleaf pine stands that had never been tilled, Markewitz et al. [37] found that the fine fraction soil C was 26.7 ± 2.2 Mg ha^{-1} (mean ± SE) from the mineral soil surface to a depth of 10 cm. At another research site that was clearcut and planted with loblolly (*Pinus taeda* L.), longleaf, and slash (*Pinus elliottii* Engelm.) pines in separate plantations, there was no significant difference in mean soil C among species; the mean soil C to a depth of 10 cm was ~44 Mg ha^{-1} at age 49 [38]. Markewitz et al. [37] and Butnor et al. [38] also reported mean soil C to deeper depths, but the deepest depths varied by study, which precluded us from comparing soil C to the deepest depth between studies. Overall, these studies highlight the importance of including coarse fraction (roots, charcoal, etc.) C in belowground estimates of C stocks and sampling soils to depths that are comparable across studies. Land use history, prescribed fire, and soil properties influence C accumulation in the soils of longleaf pine stands. For example, reforested lands are known to undergo a process of soil C accumulation, and recently reforested lands usually have fewer C stocks than mature forests in the same region and with similar soils [39]. Previous evidence also suggests that pyrogenic C (or black C) formed during low temperatures, such as that associated with low-intensity prescribed burns, is more susceptible to microbial decomposition than pyrogenic C formed at higher temperatures [40]. This highlights opportunities for research on the influence of prescribed fire on the microbial community and associated impacts on the soil C and N dynamics in longleaf pine ecosystems. Past stand conditions (e.g., old field or forested) and site preparation history also affect the productivity of longleaf pine plantations [41], further influencing C dynamics.

3.1. *Afforestation on Marginal Agricultural Lands*

Longleaf pine has been planted on marginal agricultural lands in the past (e.g., see Section 2.1.) and could be prioritized to meet long-term C objectives. Pine plantations established on cultivated lands are strong C sinks [42], but the amount of C accumulated in soils depends on the soil properties and intermediate silvicultural activities. For example, coarse-textured soils generally facilitate rapid decomposition of organic C inputs into the mineral soil by creating a highly oxidized environment that limits the increase in the stand's belowground C pool. Additionally, soils with low-activity clay mineralogy limit the amount of organic C that is adsorbed to clay particles and is protected from use by the microbial community [42]. On soils with such properties, decades may be required for newly established plantations to accrue soil C stocks such as those of old stands on soils that were never tilled. For example, Markewitz et al. [37] found that the mean soil C of longleaf pine plantations ranging from 1 to 14 years old was less than that of older stands on soils that were never tilled. Repeat sampling of soils in these same stands (24 to 37 years old in 2022) would more accurately quantify the soil C accumulation over time.

3.2. *Early and Mid-Rotation Fertilization*

In plantation management, early and mid-rotation fertilizer applications using nitrogen (N), phosphorus (P), and potassium (K) can enhance soil C stocks. For example, Butnor et al. [38] quantified soil C stocks 49 years after clearcutting, stump removal, plowing, and disking and found that plots that also received fertilization (N, P, and K) one year after planting had a greater mean C in the upper 10 cm of the mineral soil than plots with no fertilization. Fertilization, they hypothesized, increased root production and turnover and mitigated C loss due to initial stump removal and soil disturbance. In a study conducted about one year after N fertilization in a 9-year-old longleaf pine plantation, the fine root mortality was greater in plots with fertilization compared with that of plots with no fertilization [43]. The greater fine root mortality was likely associated with N-induced increases in root respiration rates and could have increased the soil C pool; the fertilization impacts on fine root biomass were not significant. At two upland sites in Georgia, Clabo et al. [44] did not detect a significant difference in mean live tree biomass between plantations that received mid-rotation fertilization and those that did not receive it. At these same sites, future research on the influence of fertilization on soil C accumulation would inform decisions about using fertilizers to increase on-site C stocks. Additional research on the use of fertilizers to enhance soil C stocks in stands that have been clearcut and that have minimal site preparation (i.e., no major soil disturbance) is also needed. Finally, the C emissions that are associated with the production and application of fertilizers should be accounted for in life cycle assessments to assess net C gain or loss [45,46].

3.3. Incorporation of Pyrogenic C into the Mineral Soil

Pyrogenic C inputs to the mineral soil are an important C pool in longleaf pine ecosystems managed with frequent fire. In a study of 14 longleaf pine stands across a broad geographic range and with frequent fire return intervals, pyrogenic C represented 5%–7% of the soil C to a depth of 1 m [47]. Butnor et al. [47] hypothesized that most of the biomass inputs from litter fall and pulses of pyrogenic C were emitted to the atmosphere during periodic fires or, in the case of pyrogenic C, redistributed via erosion. However, other studies indicated that the loss of pyrogenic C during fires is highly variable and depends on the chemical properties of the pyrogenic material and the fire intensity and duration [48] and that most eroded C does not leave its source watershed [49]. During a rotation, tilling, disking, and scarification to incorporate pyrogenic C into the soil may conflict with other management objectives such as avoiding any disturbance of the understory plant community. Alternatively, incorporating pyrogenic C that results from the incomplete combustion of on-site woody materials and/or biochar from off-site facilities into the mineral soil may be more practical during site preparation of stands that have been clearcut and do not contain desired perennial grasses and forbs. For example, logging debris could be broadcast burned and disked into the mineral soil before planting. This practice could also enhance pine survival and growth by increasing soil moisture and nutrient retention through the adsorption of water molecules and cations by charred materials [50]. In longleaf pine ecosystems managed with fire, rainfall that encounters tree leaves, branches, and stems is also enriched with dissolved organic C, of which approximately 2% can be dissolved black C [51]. Being able to quantify the fate of dissolved organic C once rainwater enters the soil would improve C models and possibly management prescriptions [52–54].

3.4. Minimize Disturbance and Utilization of Live and Dead Root Systems

In a study that examined the influence of various methods of site preparation on soil C stocks after 49 years since the planting of longleaf pine, Butnor et al. [38] showed that plantations with intensive cultivation (i.e., stump and slash removal and disking) had lower soil C stocks than those of plantations with no cultivation. These results highlight the value of woody debris and root systems and of minimizing soil disturbance to maintain or enhance soil C stocks. The C consequences of broadcast burning, no stump removal, and no disking are likely different than those of broadcast burning, no stump removal, and disking charred material into the mineral soil (as suggested in Section 3.3), though they have not yet been investigated. In conifer plantations, the successive rotations of harvesting stems and replanting can also enhance soil C [55]. Hence, comparisons of soil C stocks among planted stands should account for previous land use (e.g., whether trees are planted on marginal agricultural land or trees are planted following clearcutting).

3.5. Novel Approaches to Reduce C Emissions

Intermediate silvicultural activities such as raking for pine straw and prescribed burning can limit the amount of C that is accumulated in the soil O horizon. For example, after 30 years of prescribed burning in a mixed loblolly and longleaf pine forest, Binkley et al. [56] found that annual fires reduced O_e + O_a horizon C relative to controls. At a different research site with a two-year fire return interval, the O horizon was limited to only one year of pine needles [37]. Prescribed burning in a mixed longleaf pine and slash pine forest after six years of no burning reduced O horizon C by 87%, and it was projected that it would take six years for the O horizon C to reach pre-fire levels [57]. Targeted grazing or browsing by livestock such as goats or cattle may be a way to lengthen the fire return interval and, thereby, reduce the C emissions from prescribed burning. This assumes that the feeding by livestock would influence the fuel loads in a way that maintains floristic diversity and quality and reduces midstories while extending the frequency of the fire return interval. Alternatively, the current fire return interval could be maintained, and livestock could be used to reduce fuel loading. As climate change reduces opportunities for burning in the southeastern USA [58], targeted grazing or browsing could be used to supplement or enhance prescribed burning programs while also providing an additional revenue source for landowners. However, more research is needed to determine how these management practices would influence fire behavior and C dynamics.

4. Total Ecosystem C Dynamics

Ground-based studies of C sequestration that include repeated measurements of the total ecosystem C on the same sites are lacking in longleaf pine ecosystems. Instead of using a stock change approach to investigate the total ecosystem C sequestration, most studies in longleaf pine ecosystems measured the net ecosystem exchange (NEE) using eddy covariance techniques. Over short time periods ($\leq$3 years) that include one prescribed fire, some studies have shown that mature (~90-year-old) longleaf-pine-dominated woodlands spanning a broad edaphic gradient can be sources of C emissions when fuel consumption is considered along with NEE rates [59,60]. Additionally, these studies indicated that about 30–60 days after prescribed burning, the sites return to their pre-burn rates of net C uptake. Researchers suggested that the rapid recovery of the system is due to the timing of the prescribed fire; for example, later winter or early spring fires are quickly followed by new needle production and the regrowth of grasses as the system transitions into the growing season [59–61]. The combination of these factors contributes to the resiliency of the ecosystem to short-term perturbations such as prescribed burning. Future research comparing net C uptake and fuel consumption across sites with different fire return intervals would also be useful for informing decisions about appropriate fire return intervals for reducing C emissions.

Over time periods spanning multiple prescribed fires, drought also influences total ecosystem C dynamics. In a study of mesic and xeric longleaf pine sites over seven years, drought reduced the capacity of the sites to uptake C and was compounded when prescribed fire occurred within the two-year period of drought [61]. Despite the severe drought conditions and prescribed burning, both sites were C sinks in terms of mean annual NEE over the entire study period. However, the xeric site did not return to pre-drought levels of C uptake by the end of the study period. At these same sites, the Normalized Difference Vegetation Indices of the understory community were used in conjunction with eddy covariance estimates to better understand the ecosystem recovery from disturbance [62]. The study results indicated that the understory community of the xeric site played a greater role in C sink capacity than that of the mesic site. Not only did the xeric site have 40% less overstory basal area, but the understory took longer to recover after fire than at the mesic site. However, the understory of the xeric site was less influenced by drought conditions likely because of the adaptation to lower soil moisture availability. These results highlight the importance of considering the influence of site quality on C dynamics and how climate change may affect future C fluxes across edaphic moisture gradients.

5. Harvested Wood Products

Longleaf pine has many characteristics that are preferred for products such as flooring, molding, and furniture, which store C for long periods of time [19]. For example, longleaf pine self-prunes branches better than other southern pines, which results in straight, knot-free boles that are desirable for high-quality products [63]. The wood of longleaf pine is also strong and durable and has good product utility. Despite these characteristics and the desired products from longleaf pine trees, studies of forest C sequestration that account for the C stored in harvest wood products often use product residence time equations that are based on slash pine [27,28]. While the two species have similarities, residence time equations for longleaf pine products are needed, and new data could be used to develop these equations. There is also a need for estimates of C in specific wood products, and these could be derived by the use of tracking logs throughout the production chain.

More studies of longleaf pine ecosystems that account for the C stored in harvested wood products and the emissions from the extraction and manufacturing of wood products are needed to predict net emission reductions more accurately. When the C stored in products is accounted for, naturally regenerated stands managed at low densities for producing sawlog-sized trees could have similar net emission reductions as pine plantations managed for products with short residence times (e.g., paper products). For other southern pine species, stands managed at low densities with uneven-aged silvicultural systems have consistent aboveground C stocks and provide steady flows of sawtimber [64,65]. However, longleaf pine plantations managed on rotations for producing sawlogs were shown to have greater net emission reductions than low-density, naturally regenerated stands [28]. The tradeoff is that single-species plantations do not often provide other important societal or environmental benefits. The C emissions associated with harvesting trees, transporting roundwood and chips to mills, and the manufacturing of products also need to be considered in life cycle assessments [66]. Such assessments could compare the net C emissions of stands with frequent harvesting and low biomass removals to those of stands with infrequent and high biomass removals, which are intensities that are typical of uneven-aged and even-aged silvicultural systems, respectively.

6. Conclusions

High-quality C offset projects that balance C considerations with other ecosystem services could incentivize landowners to manage longleaf pine savannas and woodlands to meet multiple objectives. However, it will be important to understand how changing climate and disturbance regimes influence these ecosystem services. Research comparing projected C accumulation among different silvicultural approaches, while concomitantly accounting for future change, would be useful for informing management and policy decisions related to the C storage in longleaf pine ecosystems. Past studies using eddy covariance techniques showed that prescribed burning, hurricanes, and drought can influence C dynamics, and all should be considered in simulations of C accumulation. Novel approaches, such as targeted browsing or grazing, to reduce C emissions and maintain forest structure that is not prone to wildfire will have to be considered as traditional silvicultural treatments such as prescribed burning that may be limited under changing climate conditions. However, these approaches need to be evaluated before being widely implemented in longleaf pine ecosystems. Strategies for enhancing C storage in soils will also be crucial, and C accumulating in the soils of longleaf pine plantations that were formerly cultivated lands will continue to be an important sink of C depending on future land use. There is a critical need to address these gaps in our knowledge about the C dynamics in a rapidly changing climate and landscape to manage longleaf pine ecosystems more successfully for multiple social and environmental benefits.

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