CLIMATE-SMART FORESTRY AND ITS IMPLICATIONS FOR SOUTHERN SILVICULTURE

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ABSTRACT

Climate change is happening today and will continue in the future, producing many unexpected effects on our forests. In recent years, climate change has become the most critical driver for forest management, altering how we practice silviculture and forestry. Climate-Smart Forestry (CSF) is an emerging approach to sustainable forest management, with specific strategies and proactive practices aimed at promoting climate change adaptation to improve forest resilience for the benefits of neutralizing carbon emissions, sustaining productivity and provision of ecosystem services, and harmonizing environmental, social, and economic well-being. This new forestry paradigm will have significant implications for southern silviculture. In this paper, I first describe the recent rise of CSF. I then explain what is expected from CSF. Finally, I briefly discuss the implications of CSF to southern silviculture, using planted loblolly pine (*Pinus taeda*) forest management as an example.

WHAT IS CLIMATE-SMART FORESTRY (CSF)?

CSF is a new forestry paradigm that has recently emerged in response to contemporary greenhouse gas (GHG)-driven climate change. To understand how CSF differs from other forestry paradigms, I start by reviewing how forestry has evolved and then explain CSF.

Forestry has always been about managing forests to meet the needs of our society. However, society's need for forests and our perception of forests has always been changing. As a result, forestry has been an evolving concept over time. Forestry is rooted in timber management. For a long time, our society's needs from forests were timber—nothing else, which is best exemplified by this quote from President Theodore Roosevelt when he addressed the Society of American Foresters in 1903:

> The object of our forest policy is not to preserve the forests because they are beautiful . . . or because they are refuges for the wild creatures of the wilderness . . . but the making of prosperous homes (Roosevelt 1903).

Of course, this view has been long abandoned. Today, we value forests for so much more than their timber, and we care deeply about the health and integrity of our forests because forests are a critical part of the earth's life support system.

When examining its entire developmental history, forestry has experienced three paradigms: traditional forestry prior to the 1970s, ecological forestry from the 1980s to 2020, and CSF emerging around 2020. Traditional forestry was rooted in a human-centered, utilitarian view of forests, and silviculture was primarily focused on timber management. Ecological forestry was inspired by the modern environmental movement and great advances in ecology since the 1970s. Nature-based silviculture and ecosystem management approaches were developed to ensure the health and integrity of forest ecosystems and their associated goods and services. CSF is an emerging, new concept that directly responds to the threats from contemporary, GHG-driven climate change. It started in the European Union (Bowditch and others 2020, Verkerk and others 2020, Weatherall and others 2022) and has become popular in the United States in the last few years (Shephard and others 2022). I expect that CSF will promote forest

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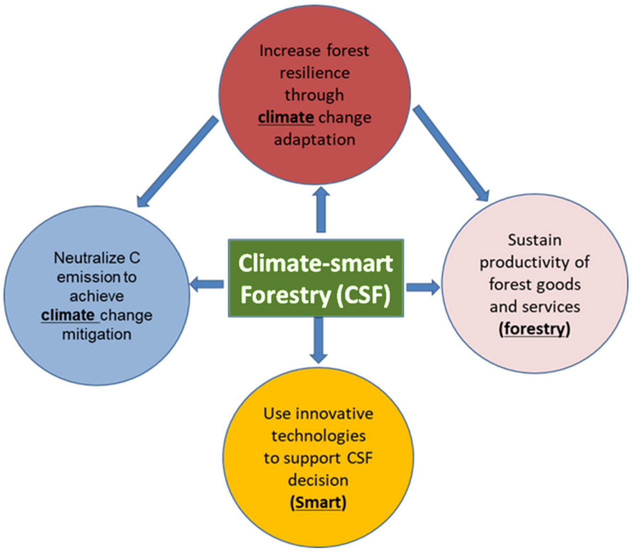

Figure 1—Climate-Smart Forestry (CSF) uses innovative technologies to support forestry decisionmaking to improve forest resilience, increase forest carbon sequestration capacity, and sustain all ecosystem goods and services for the benefit of society.

resilience through climate change adaptation so that forestry will become an important pathway for natural climate solutions (i.e., climate change mitigation).

CSF can be defined as an emerging approach to sustainable forest management, with specific strategies and proactive practices aimed at promoting climate change adaptation to improve forest resilience for the benefits of neutralizing carbon emissions, sustaining productivity and provision of ecosystem services, and harmonizing environmental, social, and economic well-being. As outlined in figure 1, the forestry part has never changed, which remains as providing goods and services to our society, but one service, climate change mitigation, is now taking the top priority. To meet this top priority, CSF must increase forest resilience through climate change adaptation while making appropriate tradeoffs with other ecosystem goods and services. To best deal with the limitations of data, the complexity of the system, and the uncertainty of climate change and its impacts, CSF must also apply new and innovative technologies to make informed management decisions. As a result, forestry has entered a new era known as CSF (fig. 1).

CSF is rooted in recent developments in climate forestry and smart forestry, and it can be viewed as a natural expansion from climate forestry with the use of new and innovative technologies (i.e., smart forestry). Climate forestry and carbon forestry are sometimes used interchangeably because they both aim at mitigating climate change through forest management. However, carbon forestry tends to have a narrower focus on carbon sequestration by planting large monocultures or managing existing forests in ways that maximize carbon storage so that carbon credits can be generated and sold on carbon markets to offset GHG emissions (Mitchell and others 2012). Climate forestry, on the other hand, manages forests to mitigate the impacts of climate change by enhancing the ability of forests to sequester carbon dioxide (CO_2) from the atmosphere, reducing GHG emissions from forest activities, and promoting the sustainable use of forest resources for environmental and socioeconomic benefits.

Smart forestry refers to the implementation of advanced digital technologies such as the Internet of Things, artificial intelligence (AI), big data analytics, and automation in the field of forestry, which is a natural evolution from digital forestry (Zhao and others 2005). It aims to optimize forestry practices by leveraging real-time data from sensors, drones, and other monitoring devices to make informed decisions that improve forest resilience, ecosystem services, and the communities that depend on them. The center of smart forestry is the development and application of forest digital twin (FDT), a virtual representation of a real-world forest ecosystem that uses real-time data to simulate the behavior and characteristics of the forest (Buonocore and others 2022), allowing the prediction of changes in stand dynamics by using early warning signals before the occurrence of unwanted events (e.g., forest decline).

WHY DO WE NEED CSF?

CSF is needed because forestry can expect to play a significant role in solving the climate change crisis. Specifically, practicing CSF can (1) improve forest resilience through climate change adaptation, (2) increase forest carbon (C) sequestration to slow down climate change (i.e., climate change mitigation), and (3) make better management decisions under climate change uncertainty.

CSF: Improve Forest Resilience through Climate Change Adaptation

Climate change has significantly affected and will more likely disrupt forest resilience (Forzieri and others 2022). As a result, CSF must help improve forest resilience through proactive management under climate change uncertainty. To do so, CSF may promote forest resistance or recovery to maintain current conditions; alternatively, CSF may also manage for changes that promote a smooth transition from the current condition to a desired alternate state (fig. 2). Which strategy to use will depend on many factors, including tree species, site conditions, and climate change scenarios.

When future climate conditions and disturbances are within their historical range of variation, CSF will promote forest resistance or recovery to maintain current forest conditions (fig. 3). Should novel climate conditions and disturbances occur, CSF would promote a smooth transition to

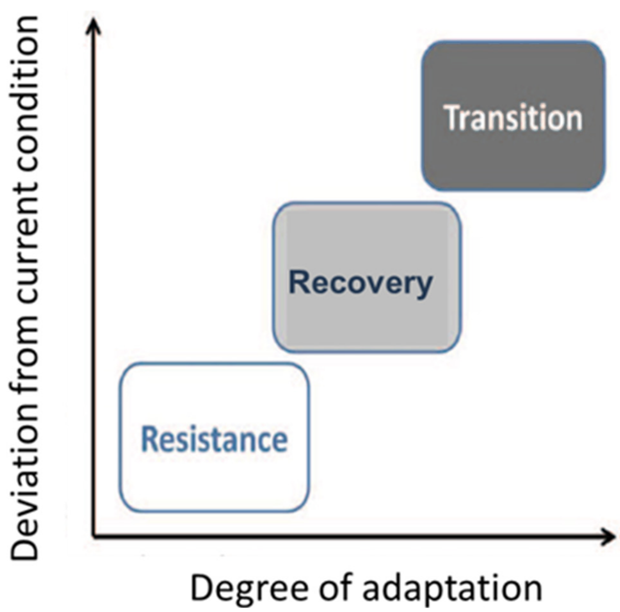

Figure 2—Forest resilience can be achieved by promoting resistance, recovery, and transition in response to climate change and disturbance. A larger deviation from the current forest condition would require a greater degree of adaptability. Modified from Nagel and others (2017).

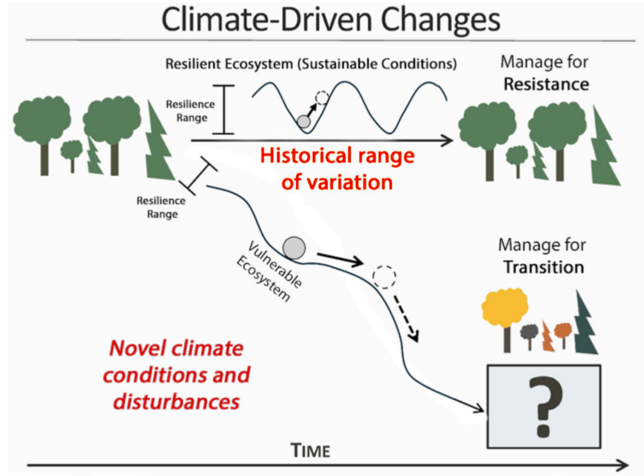

Figure 3—Hypothetical responses of current forests to climate change-driven disturbances. The resistance and/or recovery ability of current forests lead to the maintenance of current forest conditions when climate change is within the historical range of variation, but the forest will transition to a new alternate state in response to novel climate change (modified from https://www.adaptivesilviculture.org/silviculture-climate-adaptation).

desired future conditions. There is no doubt that novel climate conditions and disturbances are occurring and will continue to occur in many forests worldwide. Therefore, managing the transition becomes increasingly important, which is the most challenging aspect of CSF.

Millar and Stephenson (2015) described how management practices can influence the nature of transitions between forest types. Under novel climate conditions and disturbance, maintaining current forest conditions is not possible, and the current forest could collapse and degrade into an undesirable alternate state, resulting in the disruption of ecosystem goods and services. CSF anticipates that a change in the forest state is inevitable and takes necessary steps to ensure a smooth transition to desirable future conditions that maintain a continuous provision of ecosystem goods and services. To accomplish this desirable transition, CSF must first predict future climate conditions and disturbances, determine which suite of tree species (native or introduced) are suitable, and create a new forest community that will provide a similar structure and function to the existing forests. Each step represents a significant challenge that requires future research attention.

CSF: Increase Forest C Sequestration to Achieve Climate Change Mitigation

Terrestrial ecosystems are significant C sinks, absorbing 30 percent of our C emissions, mostly (90 percent) by forests (Keenan and Williams 2018). Therefore, a forest-based natural climate solution is an important strategy for climate change mitigation. Among the 20 natural climate solution pathways, forest pathways account for 50–70 percent of the total climate mitigation potential (Griscom and others 2017). However, realizing this potential will require increasing forest C sequestration through the help of CSF.

In general, CSF can increase forest C sequestration by following three strategies: (1) increase forest quantity (i.e., increasing afforestation and avoiding deforestation and degradation), (2) enhance forests' capacity to sequester and store carbon in situ within forest ecosystems (i.e., restoring C carrying capacity and mitigating C loss by disturbances), and (3) develop climate-smart commodities to store C *ex-situ* (i.e., increasing timber production and promoting wood utilization and substitution).

Increase forest quantity

An obvious and simple approach to increase forest C sink is to increase forest quantity in the world. This can be achieved first by increasing afforestation, which is effective but limited by competing land uses and the unsuitability of some lands for tree growth. Preventing deforestation is equally effective but requires good policies and their effective implementation. Today, deforestation remains a major problem in some countries and regions in the world, which requires international cooperation and support to incentivize forest protection. In the Southeastern United States, there is a great potential for losing forests to development, which exemplifies a significant challenge from competing land use. For example, the South Carolina Forestry Commission has estimated that about 1 million acres of forests (i.e., 7.8 percent of the total) may be lost to development by 2060 within the State[1].

Increase C storage in existent forests

Due to widespread timber exploitation and other historical human disturbances, many existent forests are currently recovering and have great C sequestration potential (CSP). In theory, the CSP of any forest can be calculated as the difference between the C carrying capacity (CCC) and the current C stock of the forest. CCC is the maximum amount of carbon capable of being stored by a forest ecosystem in a state of dynamic equilibrium under prevailing environmental conditions and natural disturbance regimes but excluding anthropogenic disturbance (Gupta and Rao 1994). For example, studies on forest CCC have been conducted at regional or national scales (Chen and others 2022, Liu and others 2014), but more research is urgently needed to determine the CCC of different forest types (Keith and others 2010) and, more importantly, to develop forestry practices to quickly realize the CSP, especially at stand and landscape scales.

Given the vast forest areas, only a small portion of forests may be actively managed in most countries in the world. Therefore, we should use a combination of passive and active restoration approaches to enhance forests' CSP. For those forests that are beyond our capacity of active management, we should protect them from disturbances, especially further human degradation. This passive forest restoration would allow natural succession to occur for the benefit of increasing forest C sequestration and storage. For those forests that can be actively managed, we should prioritize the management of stands or forest landscapes that have the most CSP, and developing stand- and landscape-specific CSF practices becomes the key to quickly realizing the CSP. Because heavily degraded forests, especially under favorable climate and site conditions, are often associated with high CSP, those stands should be first targeted for management. In the Southeastern United States, most forests that are actively managed are pine plantations. In South Carolina, pine plantations represent 24 percent of the total forest area. Therefore, how to better manage pine plantations becomes critically important to the success of CSF.

[1] Personal communication. 2023. S. Phillips, State Forester, South Carolina Forestry Commission, 5500 Broad River Road, Columbia, SC 29212.

In any forest, C storage will eventually approach the CCC, at which the forest will no longer function as a C sink. Indeed, the large C sink observed in recent years in the United States is a result of forest recovery from past forest destruction. It was reported that U.S. forests emitted 42,000 TgC (teragrams of carbon) between 1700 and 1935 due to forest clearing (agriculture, pasture, and development) but absorbed 15,000 TgC between 1935 and 2010 due to forest regrowth (Birdsey and others 2006). As this regrowth approaches the CCC, it is not clear if and how long the current rate of C sequestration will be maintained, which is another area of future research.

Under climate change, forests are likely to be subject to increasing disturbances. As a result, forest C storage is also facing a high risk of reversal (i.e., releasing CO_2 from forests to the atmosphere). More importantly, altered climate conditions and disturbance regimes could even lead to decreased CCC, forcing the release of stored C into the atmosphere during the process. In the Southeastern United States, significant stressors induced by climate change include more frequent and intense droughts and hurricanes, increased wildfire risk, and increased pressure from native and invasive pests, plants, and diseases. Therefore, more studies are needed to understand how climate-driven disturbances affect forest C storage and how this risk of reversal can be mitigated or at least factored in C-credit trading.

Ex-situ C storage through timber production, utilization, and substitution

In any stand or landscape, forest C storage would eventually saturate, reaching its C carrying capacity. At this point, further C sequestration is stopped, and the existent C stock is subject to C leakage due to natural disturbances. However, timber harvest and wood utilization can move the carbon sequestered by forests to *ex-situ* storage while increasing the CSP of the harvested forest at the same time. This represents a great opportunity for actively managed forests or plantations. To maximize this opportunity, we would (1) use innovative, climate-smart (i.e., minimizing C emission) silviculture to increase the production of timber (and/or other products), (2) promote timber and woody biomass utilization that allow long-term C storage in the products, and (3) substitute C emission-intensive products to obtain added C benefit. Previous studies have suggested that timber harvest and wood utilization, especially with the wood substitution for C emission-intensive products such as concrete and steel, can greatly increase forest C sequestration per unit area (Lippke and others 2011). However, adopting this solution would require more than silviculture and forestry.

CSF: Better Decisionmaking Empowered by AI, Intelligent Data Acquisition, and Digital Twin

To achieve CSF, we must take advantage of new and innovative technologies. Forestry decisionmaking is a complex process, especially under climate change uncertainty, which can benefit greatly from artificial intelligence (AI) (fig. 4). For example, AI can improve our predictions of future forest states by better overcoming

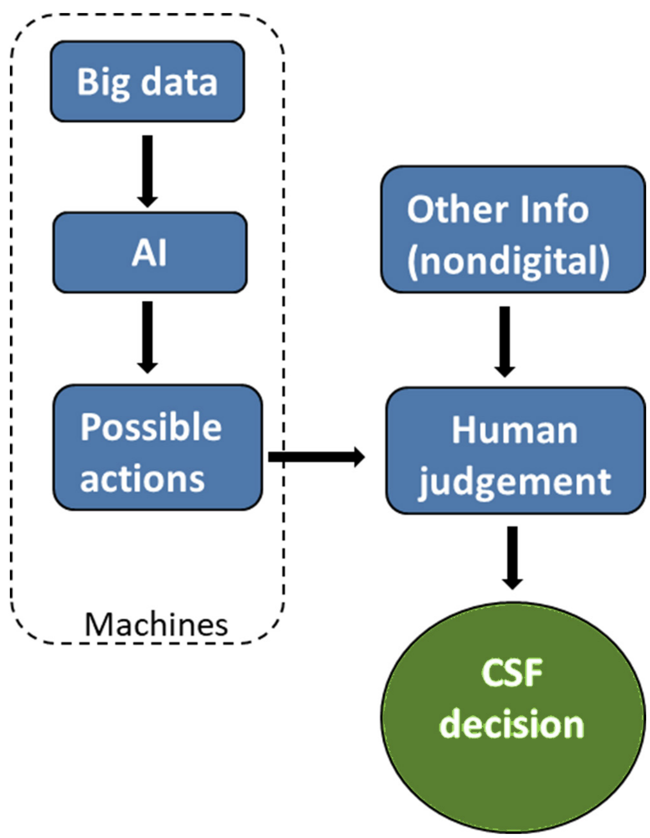

Figure 4—A Climate-Smart Forestry decisionmaking model that combines AI and human judgment [modified from Colson (2019) at https://hbr.org/2019/07/what-ai-driven-decision-making-looks-like].

data limitations, incomplete knowledge and understanding, and uncertainty in future climate change, when compared to existent modeling approaches. To be effective, CSF should adopt an evidence-based practice (EBP) that has been widely used in medicine. EBP integrates the best available research evidence, local management expertise, and landowners' values and needs into CSF decisionmaking. AI can enable efficient, objective, and systematic knowledge synthesis in the era of information explosion so that the best available research evidence is readily for CSF decisionmaking.

Better decisionmaking can only become possible with good data. CSF must develop and deploy innovative technologies in data collection. For example, a forest intelligent data acquisition system (FIDAS) powered by AI and robotics can be developed to acquire data in real time through active remote sensing. Specifically, autonomous drones with various specialty cameras and sensors onboard collect data both above and below the forest canopy with accuracy and efficiency in real time, which will greatly enrich the sparse ground data (e.g., forest inventory data) and low-resolution satellite data. It is expected that the development and application of FIDAS will revolutionize forest data collection and significantly advance forest research and management.

Better decisionmaking also needs better predictions under future climate change uncertainty. CSF can develop and apply a FDT platform to facilitate data-driven, real-time predictions. FDT is a set of virtual models that mimics the structure, composition, dynamics, and states of the physical forest, which can be constructed at any given spatial scale (from stand to global scales). The FDT platform will produce better predictions of future forest states under different scenarios of climate change and climate-driven disturbance over different temporal resolutions. By combining results from simulations and predictions with 3D virtual reality, FDT can help forest researchers and managers to visualize the states of future forests in real time. By integrating with the explainable AI method, FDT can identify and illustrate the factors that are important to the development of CSF management policies, strategies, and practices.

IMPLICATIONS OF CSF FOR SOUTHERN SILVICULTURE

CSF requires us to modify how we practice southern silviculture. In the Southeastern United States, active forest management is mostly conducted for southern pine, mainly planted loblolly pine (*Pinus taeda*). Loblolly pine plantations are one of the most globally productive timberland systems, representing 22 percent of the total forest area and an astonishing 51 percent of total forest growth in the southern region (Oswalt and others 2019). Under CSF, southern planted pine forests can be managed effectively to achieve synergy between economic goals and natural climate solutions. Therefore, planted loblolly pine forest management is used as an example to illustrate some possible changes in silviculture under CSF.

Manage for Forest Resilience

Maintaining forest health and productivity is of paramount importance under climate change. Therefore, CSF must promote forest resilience under climate change uncertainty. To do so, current silvicultural practices must be adapted to major stressors under climate change [e.g., temperature rise, drought, fire, and southern pine beetle (*Dendroctonus frontalis*) outbreaks]. Using a landscape-level, instead of stand-level, management approach, silvicultural practices developed under CSF should aim to 1) increase species and structural diversity (stands of different ages or structures), 2) improve functional complexity (diversity and redundancy of tree functional types), and 3) optimize spatial connectivity of forest stands in terms of seed dispersal and establishment in forested landscapes (Messier and others 2019).

For example, we can improve the functional complexity of a planted loblolly forest-dominated landscape in two ways. First, we may increase the presence of other native tree species with different functional attributes. Specific silvicultural practices would include 1) promoting live oak (*Quercus virginiana*) and slash pine

Figure 5—An illustration of forest resilience in two forested landscapes with different functional complexity (diversity and redundancy of tree functional types). Modified from Messier and others (2019).

(*Pinus elliottii*) in coastal areas to increase forest resilience in response to salt spray and sea-level rise, or 2) increasing longleaf pine (*P. palustris*) component to better cope with increasing activities of drought, fire, and southern pine beetles. Second, we may introduce new functional attributes not currently present in the landscape. Specific silvicultural practices would include 1) expanding slash pine northward in anticipating temperature rise, or 2) promoting the northern expansion of shortleaf pine (*P. echinata*) to cope with temperature rise and increased fire frequency.

It has been conceptualized that improving functional complexity in forested landscapes would increase forest resilience (fig. 5). A landscape dominated by planted loblolly pine forests may be vulnerable to climate change, but a landscape with planted pine and many other stand types, when mixed in a desired proportion and spatial pattern, is likely resilient to climate change. For example, under a mean fire frequency of 3 years, a fire-free interval of 15 years would only occur once every 1,000 years based on the equations of Hoffmann and others (2012). Given the specific fire-free interval required for canopy recruitment of different tree species in southern forests, an increase in wildfire frequency to ≤4

Figure 6—An example illustrating that functional complexity promoted forest resilience under a novel disturbance: American chestnut-dominated forests are replaced by oak-dominated forests due to the exotic invasive species— chestnut blight.

years due to climate change would practically eliminate loblolly pine, oaks, and other hardwood forests in the landscape. These forests would transition to longleaf, shortleaf, and slash pine forests if these species were present in the landscape. As a result, the functional complexity of a forest landscape becomes a prerequisite to this transition under increased fire frequency induced by climate change.

A good example showing how functional complexity promotes forest resilience in response to a novel disturbance is the transition of American chestnut (*Castanea dentata*)-dominated forests to oak (*Quercus* spp.)-dominated forests because of a novel disturbance—chestnut blight (fig. 6). The example demonstrated the inherent resilience of eastern hardwood forests, probably due to their functional diversity and redundancy of tree species. Therefore, it is of great importance for climate-smart silviculture to promote functional diversity at both stand and landscape scales.

Manage for Forest C Sequestration

One of the key CSF objectives is leveraging forest management as a natural climate solution. Under CSF, planted loblolly pine forest management must emphasize C sequestration. Enhancing forest C sinks of planted southern pine forests can help our nation to meet emissions-related goals such as the Paris Climate Agreement (Grassi and others 2017). To do so, we can build on our comprehensive understanding of planted southern pine forest C pools and fluxes (Kinerson and others 1977).

Increase timber production

Planted loblolly pine forest management has been focused on increasing timber production through tree improvement and innovative silvicultural practices. For the 60 years from 1940 to 2000, silvicultural treatment and tree improvement increased timber production of planted loblolly pine forests by about 400 percent (Fox and others 2007). Therefore, continuing to improve on our past success in loblolly pine silviculture and tree improvement is critical for increasing C sequestration.

Develop climate-smart practices

To maximize timber production, even-aged management with short rotations has been widely applied to planted loblolly pine forests. However, following a clearcut, the stand initiation can be a significant C source for up to 10 years. To minimize this C source, we may want to explore if there are better alternatives to this popular practice. For example, future studies should examine the potential C benefit by using a longer rotation with even-aged management or by implementing uneven-aged management.

Develop climate-smart commodities

How we use the harvested timber can significantly impact the potential of planted southern pine forests as a C sink. For example, the use of mass timber in building construction can achieve both C substitute and long-term C storage. Mass timber can substitute concrete and steel, reducing C emissions from fossil fuels. The C contained in the mass timber can also be stored in the built environment for the long term when compared with other timber uses. Similarly, easily decomposable woody biomass in forests is a major C source, and its conversion to biofuel and biochar could significantly enhance forests' capacity as a natural climate solution. In addition to significantly reducing forest decomposition, biofuel is a source of renewable energy and can substitute fossil fuel, which reduces C emissions. The application of biochar can improve soil properties and potentially reduce the use of fertilizers, another way of C substitution that reduces C emission. Biochar C can also be stored long term in soil, increasing soil C storage.

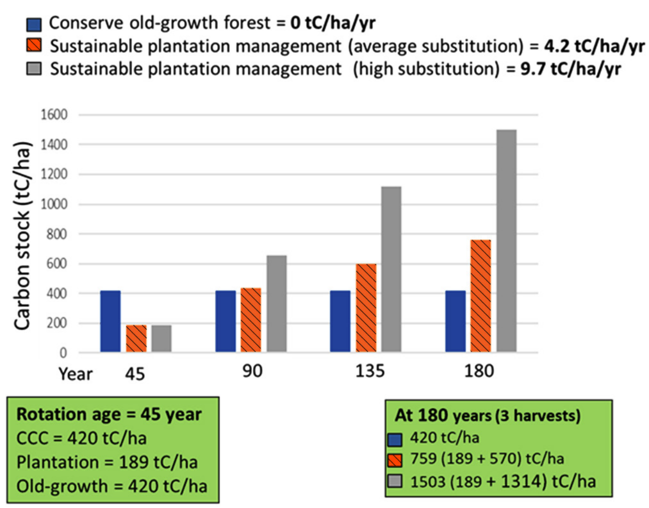

Figure 7—The impact of management and wood-use alternatives on total carbon mitigation. Carbon storage through timber utilization and substitution (i.e., *ex-situ* storage) greatly increases the capacity of forest carbon sinks. This figure is reconstructed from the data of table 1 of Lippke and others (2011), assuming the old-growth forest has a carbon stock at the carrying capacity (CCC) of 420 tC/ha, and the sustainably managed plantation has a carbon stock of 189 tC/ha at the rotation age of 45. The three scenarios are 1) conserving the old-growth forest, 2) sustainably managing the plantation with average substitution, and 3) sustainably managing the plantation with high substitution. At 180 years after three harvests, *in-situ* carbon stock is 420, 189, and 189 tC/ha, *ex-situ* carbon stock is 0, 570, and 1314 tC/ha, and carbon sequestration rate is 0, 4.2, 9.7 tC/ha/year.

Lippke and others (2011) illustrated the potential of *ex-situ* C storage by comparing an old-growth forest and a managed 45-year rotation planted forest established on similar climate and site conditions (fig. 7). The old-growth forest had already reached its CCC (the maximum C stock) at 420 tC/ha, so it would no longer sequester any more C. The sustainably managed planted forest had a much lower *in-situ* C storage at the rotation age of 45, which was 189 tC/ha. However, the plantation was harvested once every 45 years, and the *ex-situ* C storage of the planted forest is realized due to substitution and long-term storage after each timber harvest. As a result, compared to land consistently maintained as old growth, the land used for timber management (i.e., the sustainably managed planted forest) would have created an additional C sequestration at 4.2 (average substitution) and 9.7 (high substitution) tC/ha/year for the next 135 years (after three harvests) at the time when the fourth harvest is conducted (fig. 7).

CONCLUSIONS

CSF is a new forestry paradigm that is motivated by our desire to use forests as a natural climate solution and empowered by innovative technologies such as AI, intelligent data acquisition systems, and FDT.

CSF emphasizes increasing forest C sequestration to slow down future climate change (i.e., climate change mitigation) but must do so to ensure forest resilience through climate change adaptation to sustain all ecosystem services.

Because land availability limits the increase of forest areas and the inherent CCC and natural disturbances limit the *in-situ* forest C storage in existent forests, *ex-situ* C storage must be encouraged through timber production, utilization, and substitution.

CSF will change how we practice silviculture in the Southeastern United States. With some modification and development, planted loblolly pine forest management is well positioned to help achieve CSF.

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