CHAPTER 2

Forest Management for Carbon Removal and Storage

SUMMARY

Forests provide critical climate-mitigation services. In *The Long-Term Strategy of the United States Pathway to Net-Zero Greenhouse Gas Emissions by 2050* report, enhancing the forest land sink is an integral component of scaling up CO_2 removal for negative emissions [1]. In this chapter, we adopt this framing and consider that new forest-management activities that lead to net atmospheric reductions in CO_2 are viable CO_2-removal pathways. Forest management is a well-studied road to removal with strong scientific underpinnings and an experienced knowledge base of foresters to implement management practices.

The durability of forests as carbon sinks in the future is a pressing concern. Climate change is increasing the carbon emissions of forests through disturbances like wildfire, pest and pathogen outbreaks, and hurricanes. Loss of forest-carbon stocks—and the resulting CO_2 emissions to the atmosphere—will appear in the National carbon budget and increase the challenge of reaching net-zero.

Growing evidence indicates that "climate-smart" forest-management practices may increase forest-carbon durability and reduce forest emissions. Additionally, forest management has benefits beyond CO_2 removal and storage. Forests are vital for wildlife and biodiversity; they provide food, fuel, timber, and fiber to society; they clean our air and water; and they are of immense cultural, aesthetic, recreational, and spiritual value.

The variety and importance of the suite of services forests provide creates numerous opportunities, but also numerous challenges, for managing the Nation's forests. Forest management for singular purposes will nearly always lead to trade-offs among forest services; for this reason, the US Department of Agriculture (USDA) recognizes that there is no singular one-size-fits-all climate-smart forest strategy to pursue across the Nation's forests. Instead, forest-management strategies should be place-based, flexible, and locally led and account for the other forest benefits or potential adverse impacts [2, 3].

Following this ethos, we present three case studies that represent region-specific examples of forest management for carbon removal and storage that are place-based and climate-smart. We selected management options that are tailored to regional land-use legacies and strengths of current timber markets, are likely to make forests more resilient to future unpredictable weather and climate events, and are geared toward increasing carbon-removal capacity and the durability of stored carbon.

CHAPTER SCOPE

This chapter reviews the extensive literature on the relationship between forest management and carbon removal and storage and presents analysis of forest CO_2 removal options for three regional case studies.

- Section 1 is an overview of forest carbon cycling and the impact of historical forest-management decisions on the carbon-removal capacity of US forests today.
- Section 2 reviews existing knowledge on the wide variety of forest-management options for CO_2 removal and highlights how our case studies build and expand current knowledge.
- Section 3 presents three case studies of "climate smart" forest management for southern New England, the west, and the southeastern United States.

Key Findings

Policymakers or forest managers have three primary levers they can pull to increase forest carbon: (1) increasing the total forestland area of the Nation, (2) increasing the rate at which forests remove CO_2 from the atmosphere, and (3) increasing the durability of forest-carbon storage. Importantly, forest-management practices can pull multiple levers simultaneously while also positively influencing other forest services (**Section 1**). In this chapter, we review and build from the extensive knowledge of forestland management for CO_2 removal and demonstrate through three case studies how regionally specific forest-management practices provide viable roads to removal. *We find through these three case studies the total forest CO_2-removal potential is between 1.5 and 1.8 billion tonnes of CO_2 equivalent (CO_2e) by 2050.*

Prior research has consistently shown that increasing the Nation's total forestland through tree planting is an efficient and scalable CO_2-removal option. Multiple national studies estimate newly planted trees could annually remove between 27.6 and 314.2 million metric tonnes of CO_2e, with many identifying the southeastern United States as a region of opportunity [4-8]. The wide variation in CO_2-removal estimates emphasizes the challenges in projecting the impact of forest-management actions across such an ecologically and economically diverse Nation, while also emphasizing the vast potential for this strategy (Section 2).

- Building from these prior studies, in **Section 3.1** we explore *how planting 2.1 million hectares (ha) (5.2 million acres) of the southeastern United States in 2025 may provide total CO_2-removal between 1.51 and 1.78 billion tonnes of CO_2e by 2050*. Planting high-density pine forests for restoration can remove 71.14 million tonnes of CO_2e per year at a price of \$1.22/tonne CO_2e. Alternatively, planting low-density pine forests for commercial plantations on the same land base can remove 67.27 million tonnes of CO_2e per year while generating a net revenue of \$13.80/tonne CO_2e.

Wildfire is the leading cause of forest emissions for the Nation's forests today. From 2017–2021, wildfires emitted an average of 140.8 million tonnes of CO_2 annually, and forests in six western states are now net carbon sources [9]. There is widespread agreement that implementing "fire-smart" management in dry western forests may be one of the most important practices for protecting the durability of their carbon stocks [10-12] and may increase the rate at which these forest remove CO_2 (**Section 2**).

- In Section 3.2, we explore *how applying fire-resilience-based forest-management treatments to 0.48 million ha (1.19 million acres) of dry forests in the western United States' wildland-urban interface may provide up to 16.21 million tonnes of cumulative CO_2e by 2050 by abating wildfire impacts on forest carbon*. If limited to a maximum cost of \$200/tonne CO_2e, we could achieve this amount of CO_2 removal at an average cost of \$47/tonne and an annualized rate of 0.64 million tonnes of CO_2e between 2025 and 2050.

The current health and condition of the Nation's forests today directly stem from historical management decisions (Section 1.1). Adopting regionally appropriate silvicultural practices can potentially increase the rate at which forests remove CO_2 and increase the durability of forest-carbon stocks from large losses after natural disturbances, as well as maintain supplies of wood products and potentially provide economic incentives to prevent the sale of forestlands for development [13-16] (**Section 2**).

- In Section 3.3, we explore *how applying regeneration-focused silviculture prescriptions across 2.6 million ha (6.4 million acres) of hardwood forests of southern New England and southeastern New York could lead to net climate benefits of 67.84 million tonnes of CO_2e removal relative to passively managing these forests with no future harvests*. This drawdown can be achieved while generating a net revenue of \$37.46/tonne CO_2e through timber sales. We note, however, that this finding includes accounting for wood-product substitution for fossil-based energy and materials and that extreme natural disturbances like drought, wind, and pest and disease outbreaks in the region will continue. If we exclude carbon gains from the substitution benefits of wood products, regeneration-focused management would lead to a cumulative loss of 241.38 million tonnes of CO_2e in forest carbon stocks by 2050 relative to no harvests. Regeneration-focused management would achieve net gains of carbon in forests and wood products after 2085.

Key Assumptions, Unknowns, and Challenges

- *These case studies are by no means all the available synergistic opportunities for CO_2 removal via forest management*, but instead are three that demonstrate the importance of incorporating regional nuances—including ecological context, cultural characteristics, and socioeconomic opportunities—into regional forest management planning. We emphasize that there are likely many other regional opportunities for forest management and CO_2 removal and storage.
- *Forest soils are important carbon stores.* A rich body of knowledge suggests that soil carbon stocks will be responsive to forest management; however, empirical support for these expectations is less conclusive and is an area of further research [17] (**Box 2-4**). For these reasons, we only account for soil carbon changes in our southeastern case study (**Section 3.1**).
- *Novel long-lived wood-product markets hold vast potential.* Building markets for long-lived and durable wood products like biochar and cross-laminated timber could provide vast carbon-storage potential [18-20], but there are still many uncertainties surrounding the sustainability, durability, and accounting methods of the climate benefits of these products [21-24]. We do account for carbon storage in novel wood products for our southeastern (Section 3.1) and northeastern (Section 3.2) case studies.

1. Overview of Forest Carbon

Trees and other forest vegetation are living "direct air capture (DAC) machines" powered through renewable solar energy and transforming CO_2 into organic carbon molecules. Forests gain carbon as vegetation captures atmospheric CO_2 during photosynthesis and transforms it into organic carbon. Trees and forest vegetation are also both carbon-storage facilities that hold carbon in long-lived plant tissues and carbon pipelines that transport carbon into forest soils. To measure gains and losses in forest carbon, scientists divide forest-carbon storage into various "carbon pools." One of the most important carbon pools in forests is living plant tissue. Plants, especially forest trees, store most of their carbon in woody plant tissues like tree trunks, roots, and large branches. Plants directly add carbon into the soils through their roots. A portion of the carbon in living plant tissues will accumulate as leaf litter and coarse woody debris, eventually decaying and feeding the forest soil-carbon pool. In the US Environmental Protection Agency's (EPA's) 2023 report, the US Inventory of greenhouse gases (GHGs) estimated that forest living and dead vegetation and forest soils were, at the time of the report, storing approximately 56.95 billion tonnes of carbon (**Figure 2-1**) [25] .

Forests also emit carbon. When plants die or soils are disturbed, carbon in these pools returns to the atmosphere. Tracking the growth and death of living trees is easy to measure and model relative to other forest-carbon pools, and this forest-carbon pool is the most susceptible to carbon

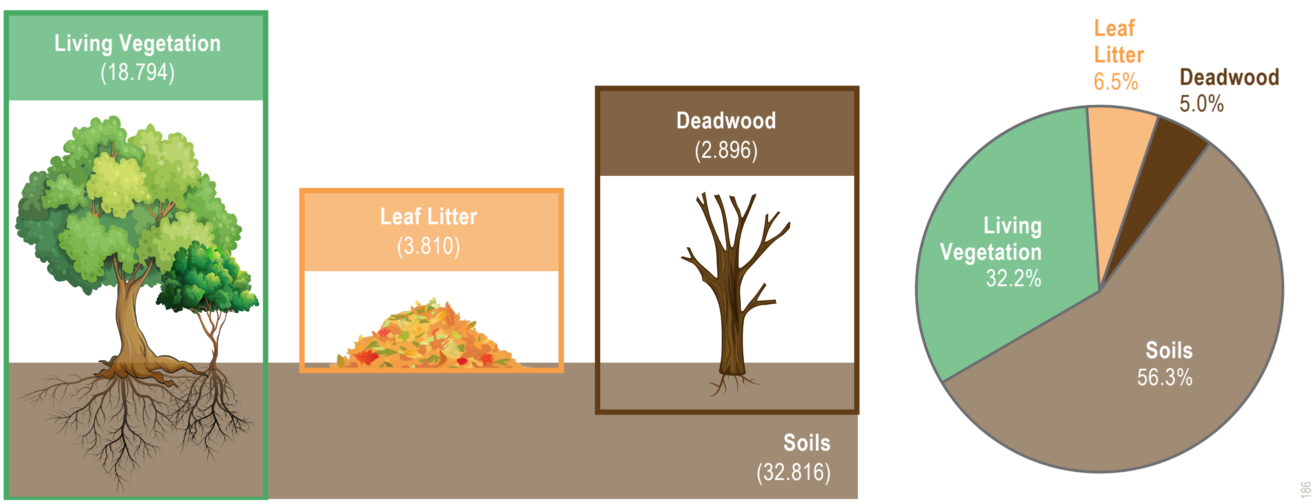


Figure 2-1. *Forest carbon pools (billion tonnes of carbon). The US Inventory of greenhouse gases (GHGs) estimates that across the Nation, approximately one-third of forest carbon is stored in living trees and other plants while over one-half is stored in forest soils [9]. The exact proportion of carbon stored in forest-carbon pools varies based on climate, tree species, and soil type of a given forest region, as well as how humans manage a given forest tract. Images courtesy Jane Hawkey, Dylan Taillie, Tracey Saxby, Joanna Woerner, Jane Thomas; Integration and Application Network [26]*

loss, via anthropogenic and natural disturbances. Forest vegetation and soil organisms also lose CO_2 via respiration, but these emissions are fundamental to healthy tree growth and maintenance and thus are not a management opportunity. In **Section 2**, we review the major drivers of forest-carbon emissions, how these vary across forested regions, and their implications for forest-management decisions. From 1990 to 2021, forests in the United States accrued more CO_2 through photosynthesis than they emitted from tree disturbance and death, making them a net carbon sink [9, 27]. The US Inventory of GHGs reported that, in 2021, forests accrued 161.6 million tonnes of carbon (592.5 million tonnes of CO_2e), with forest vegetation accruing approximately 83% of the total carbon gains in forests [9].

Forest CO_2-removal rates vary among states (**Figure 2-2a**) and through time (**Figure 2-2b**). Net annual variations in CO_2 removal are now predominantly driven by the frequency and severity of western wildfires. In the past 5 years, average forest-wildfire emissions are 140.8 million tonnes of CO_2e each year, which includes loss of forest-carbon stocks and emissions of other GHGs, including nitrous oxide and methane [9]. States with net forest emissions in 2021 all had extremely dangerous, devastating, and widespread wildfires (Figure 087a). Increasing healthy, fire-resilient forest-management practices in regions with high fire potential can potentially reduce total wildfire carbon emissions, save communities and human lives, and prevent these forests from becoming CO_2 sources, which we explore in **Section 3.2**

After wildfire, the second leading cause of forest-carbon emissions is timber harvest [9, 27]. However, the impact of timber harvesting on forest-carbon loss is different from other forest disturbances. For example, deforestation releases much of the forest's carbon to the atmosphere and neutralizes a forest's future ability to capture or store carbon (**Section 2**). Alternatively, harvesting trees for wood products can store carbon "out of the forest" in wood products [9, 28]. In 2021, the US Inventory of GHGs estimated that harvested wood products stored approximately 2.8 billion metric tonnes of CO_2e [9]. The duration of carbon storage in wood products will depend on the type of wood product and how humans dispose of the wood products. Relatively short-lived wood products like pallets and paper may last less than a decade,

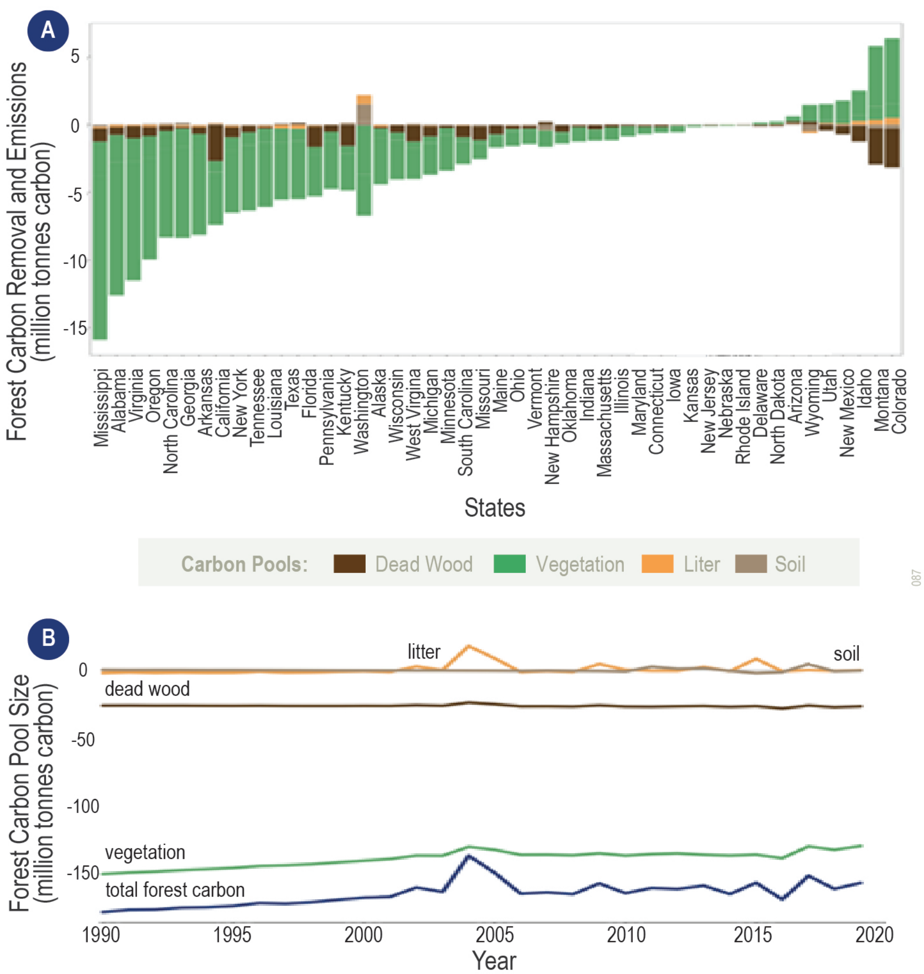


Figure 2-2. *Forests in the United States, on average, remove more CO_2 than they emit to the atmosphere. The United States Inventory of GHGs [1] reported high variation in CO_2 accrual or loss in forests found in different states in 2019 (A) and over the past three decades for all forests in the Nation (B). Negative values in both panels indicate net carbon gains in forest-carbon pools as forests remove more CO_2 from the atmosphere. Positive values indicate net carbon losses in forests as carbon pools emit carbon to the atmosphere.*

while long-lived wood products like building frames can last for over a century. Novel and emerging markets for wood products, like cross laminate timber and biochar, may lead to longer-term carbon-storage and may have net carbon benefits if they provide building substitutes for more carbon-intensive products, such as steel and concrete. We discuss these possibilities in **Section 3** and **Chapter 6**.

The Nation's forests are diverse in terms of the tree species common in the region (**Figure 2-3a**) and the type of forest owner (**Figure 2-3b**). Private forests, including a wide variety of individual, family, and corporate ownerships, predominate in the eastern United States, while federally managed forests dominate the western United States. Tribal nations have sovereignty over more than two million acres of land, and more than 300 tribes steward forestland with the majority of this forested land being located in the western United States [29].

1.1 Historical Forest Management

Current national planning efforts to stimulate and increase CO_2 sequestration and storage within forested ecosystems must take into account how historical land-use activities affect current forest-carbon stocks and storage capacity (**Box 2-1**). During the 18th and 19th centuries, colonists expanding westward violently separated Indigenous communities from the forests they stewarded, allowing the growing European-American settler population to clear forests to create farmlands and pasturelands and to harvest timber for building materials and heating homes [29]. Deforestation and harvesting rates peaked around the turn of the 20th century, resulting in an estimated total loss of approximately 27 billion tonnes of carbon (99 billion tonnes of CO_2e) [31, 32].

Since 1900, new trees have grown on much of the cleared forestland—either through unassisted tree recruitment or intentional planting for commercial plantation forests [33]. In some areas, such as the southeastern United States, forestry activities are vital components of the regional economy. In these areas, the forest sector manages forests to provide critical wood products to national and international consumers and, through management decisions, influences the size of forest-carbon stocks and the rate at which future forests remove carbon. However, in other areas, such as much of the western United States, timber markets and harvesting infrastructure have declined, which poses logistical challenges for using harvested wood products in ways that reduce carbon emissions to the atmosphere. Consideration of historical forest-management decisions highlights two contemporary forest-management options: first, we have vast areas of the Nation that were once forested and represent opportunities for large-scale reforestation campaigns. Second, the carbon stocks and removal capacity of today's forests are a function of historical management decisions, and in many regions, the legacy of poor management decisions could be corrected through more scientifically informed management decisions (Box 2-1).

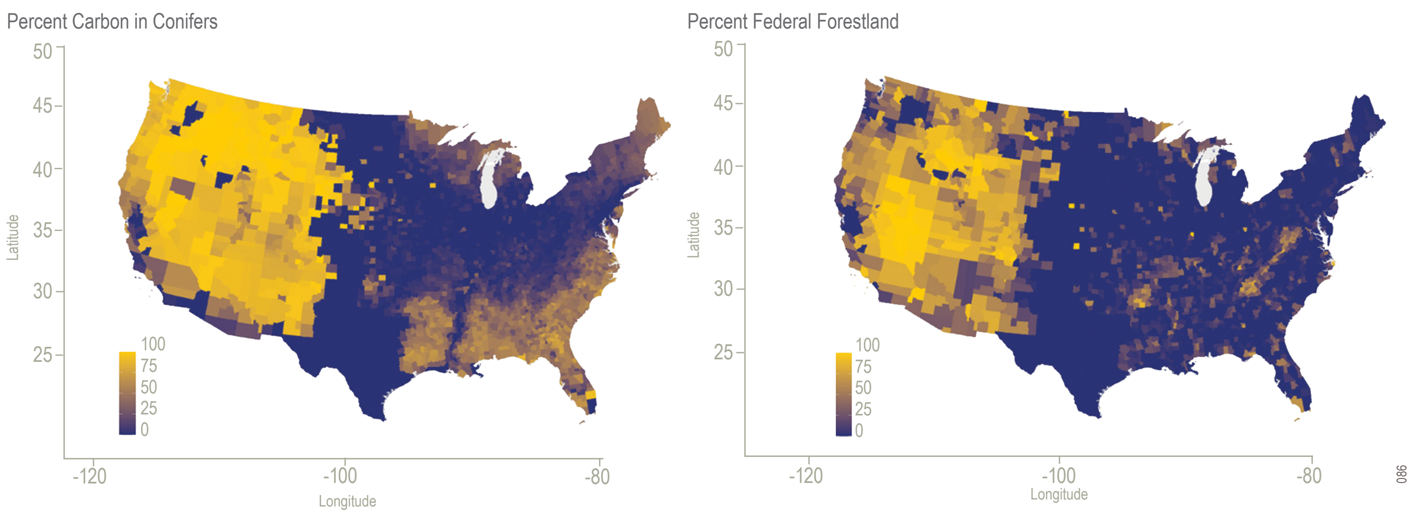


Figure 2-3. *Forests across the United States are highly variable in the types of trees that grow in them (A) and the people who own and make forest-management decisions (B). Coniferous tree species are relatively more abundant and store a higher proportion of forest carbon than deciduous tree species in forests of the western and southeastern United States. Federal agencies own and manage a higher proportion of forestlands in the western United States relative to the eastern United States, where private forest ownership is more common (B). Maps derived from the US Forest Service (USFS) Forest Inventory and Analysis (FIA) National Program using the most recent inventory cycle for each state [30].*

BOX 2-1

Future Consequences of Historical Forest Management

Historical forest management has three important consequences for the rate at which forests remove CO2 from the atmosphere and the size of current forest-carbon pools.

1) The current carbon stocks and rates of CO_2 removal are predominantly driven by current forest age. Forest stands with younger trees remove CO_2 from the atmosphere at relatively higher rates than ecologically similar forest stands with older trees. However, older forests store more total carbon than younger forests. Forests in the United States are now mostly middle-aged, closed-canopy “second growth forests” that are still recovering from 18th and 19th century deforestation activities. On average, the middle-aged forests are nearing their maximum rates of CO_2 removal and may continue removing CO_2 at declining rates through time [7, 31, 32].
2) The total forestland base is marginally growing each year but is not as large as historical forest-cover prior to widespread European colonial deforestation in the 18th and 19th centuries. On average, nationally, the rate of reforestation is greater than the rate of deforestation, which is ultimately contributing to annual net carbon gains from an increasing forestland base [6, 25, 27, 29, 34, 35].
3) The total carbon stocks of most dry western forestlands are higher than they were before human harvesting activities. Heavy timber-harvesting activities coupled with a century of fire-suppression management policies have led to increased forest biomass and carbon stocks beyond what would have existed in the absence of fire-suppression management [36, 37]. Today, the higher forest biomass, hotter climates, and more frequent droughts induced by climate change, increase risks of catastrophic, stand-replacing fires in the region.

1.2 Future Trajectories of Forest-Carbon Storage

While the Nation’s forests are currently net carbon sinks overall (Figure 087), changing climates could convert forests to net carbon sources. Policymakers or forest managers have three primary levers they can pull to increase future forest carbon: (1) increasing the total forestland area of the United States, (2) increasing the rate at which forests remove CO_2 from the atmosphere, and (3) increasing the durability of forest-carbon storage. Forest-management practices tailored to specific regions can differentially pull these levers to achieve CO_2 removal. We review each lever within this section, providing information on current trends and how continuation of these trends is projected to impact future forest-carbon stocks.

Trends in Changing Forestland Area

The total carbon-storage potential of forestland is a direct function of the total area of forestland. Increases in forestland area increase the potential for forests to sequester and store carbon, while decreases in forestland area decrease this potential. In any given year, the Unites States gains and loses forested parcels as humans decide to plant new forests in some areas and deforest other areas. Overall, the United States is gaining more forests than it is losing [6, 7, 9, 27, 29, 34, 35] (**Box 2-2**). However, regional trends vary substantially, with some regions like the eastern Unites States (New England in particular) seeing greater rates of deforestation than reforestation through time [38, 39].

A complex set of socioeconomic drivers leads to deforestation, including but not limited to a forest’s economic value, human population growth, and public cultural values. Loss of forestland to development is spatially heterogenous, is often concentrated near existing urban areas and along transportation corridors, and is sensitive to global economic variability [40]. Projecting future land-use change and forest-conversion rates is challenging [41]. However, one estimate has suggested that, if the United States reduced all deforestation by 2025, carbon sequestration rates could increase ~12% (from 323 to 362 million tonnes of CO_2e) by 2050 relative to a “business as usual” projection of national deforestation rates [6].

Protecting existing forestlands and incentivizing private landowners to keep forestlands as forests (or to reforest lands that were once forests) can sustain or increase the total forestland base [36, 37]. Deforestation is the single largest source of carbon emissions from US forestlands (Box 2-2). Future policies will also have to wrestle with how to develop and foster land-use planning that can accommodate building and expanding the Nation's technological infrastructure for renewable energy and climate mitigation, while also protecting existing forestlands and other ecosystems and expanding the forestland base [44, 45].

Because deforestation leads to large carbon losses and declines in ecosystem services and biodiversity, the modeling throughout this report does not convert existing forestlands for development of agriculture, direct air capture with storage (DACS), or biomass carbon removal and storage (BiCRS) facilities. In **Section 3**, we model how increasing the total forestland base through pine planting in the southeastern United States would increase forest CO_2 removal and could provide novel wood products to support regional and national economies

Trends in Rates of Forest CO_2 Removal

Rates of forest CO_2 removal are a function of how efficiently trees remove CO_2 and the total number of trees in the forest. Trees, as the primary "DAC machinery" in forests can be more or less efficient depending on their overall health and age, the type of trees, and the climate in which those trees grow. One of the best ways to ensure that forest "machinery" is functioning efficiently is to promote forest health; pollutants, wildfires, insect and disease outbreaks, drought, and windstorms can prevent or slow the rate of forest CO_2 removal by damaging or destroying tree tissues.

Currently, the size of the Nation's forestland base and current tree CO_2-removal efficiency are sufficient to make forests a

BOX 2-2

Prevention of Deforestation: the Need for Public Support

Conversion of forests to agricultural or developed lands is the single largest source of carbon emissions from the Nation's current forest carbon stores. Deforestation led to an estimated 144.4 million tonnes of CO_2e emissions in 2021 as forests were replaced by human settlements (63.4 million tonnes of CO_2e), croplands (48.5 million tonnes of CO_2e), and grasslands (19.4 million tonnes of CO_2e) [25]. Vegetation carbon-density values for common US forest types typically range from approximately 200 to 1000 tonnes of CO_2e per ha. The aboveground stores of carbon, such as living trees, are lost from the land immediately upon conversion, while belowground stores, such as tree roots and soil organic carbon (SOC) are incrementally lost over the next couple of decades to the atmosphere (Figure 085).

Deforestation trends are set to continue in some regions without concerted efforts to protect forestlands [42, 43]. Policies and economic incentives that prevent deforestation have high potential to sustain some of our most carbon-dense landscapes across much of the United States [34]. Keeping forestlands forested also maintains their annual net uptake of CO_2 from the atmosphere, which is lost when converted to human settlement. However, the Nation's land-use planners face a daunting challenge ahead. Decarbonizing our economy and mitigating climate change will demand new renewable-energy and climate-mitigation infrastructure. As we decide where to expand and site new facilities, we also need to protect our existing forests, which are important carbon-storage and-removal facilities [44, 45].

Rather than focusing on deforestation, public opinion has focused instead on environmental concerns of US forest management, especially harvesting for pulp and timber [46, 47]. By contrast to deforestation, however, harvesting sustains some aboveground carbon stores (e.g., dead wood) and regrows living trees, while also protecting much of the belowground carbon stores. Some harvested timber also provides long-term carbon storage out of the forest when that timber is used in long-lived wood products like furniture or construction materials [25, 28]. When the objective is to limit carbon losses to the atmosphere and to sustain CO_2 removals, protection of the Nation's forests from deforestation—especially private forestlands that appear most at risk—is a priority.

net carbon sink each year [25]. This net sink exists despite large carbon emissions from deforestation (Box 2-2) and massive declines in vegetation-based forest-carbon pools when trees die from wildfire, insect and disease outbreaks, or other climate stressors.

Without significant improvements in forest management and silviculture for increased resilience to climate-change stressors, we should not count on the Nation's forests to remain a net carbon sink. Specifically, while forests are projected to remain net carbon sinks through 2050 [6, 7], the rate of forest CO_2 removal is projected to decline as forest health declines and trees die from increasing drought, wildfire, and insect and pathogen outbreaks [6, 7, 29, 32, 48]. The US Forest Service (USFS) reported that between 2006 and 2016, the average annual net forest growth declined owing to a doubling of the average annual forest mortality stemming from natural death of aging trees and increased tree mortality from wildfires, droughts, and insect and disease infestations [29]. Other climate-related stressors (e.g., ground-level ozone (O3) pollution) are also widely believed to have large impacts on tree health [49], but we have limited empirical data to track the magnitude of their impact on forest vegetation [50]. National estimates suggest that forest-carbon sequestration rates may decline by ~33% between 2030 and 2050 under current rates of forest growth and disturbance [6, 7].

National estimates of the decline of forest CO_2-removal rates vary dramatically by region. Projected carbon-sequestration rates for forests of the eastern Unites States and Pacific Northwest in 2050 are between 65% and 85% of 2015 sequestration levels. Carbon-sequestration rates for western forests in 2030 are projected to decline to near zero [6]. After 2030, western forests may reverse from a net carbon sink to a net carbon source [6]. Even considering the positive effects on forest growth of projected climate warming and nitrogen and CO_2 fertilization, aging North American temperate forests facing multiple stressors like drought, high temperatures, insects, and diseases may only sequester a quarter of the CO_2 they sequester today by the end of the 22nd century [51].

Just as operators of a DACS facility must perform annual maintenance and replace parts of their machinery, so must forest managers maintain their forests if they wish to keep them healthy and efficient at removing CO_2 from the atmosphere (**Box 2-3**). In **Section 3**, we discuss how management strategies tailored to regional ecological and economic conditions can improve forest health.

Trends in Durability of Forest-Carbon Storage

As described in the earlier section, the flow of carbon between forest-carbon pools and the atmosphere is dynamic (**Section 1**). Forests can lose carbon stored in vegetation and soils from unplanned disturbances, such as wildfire, wind, ice storms, and outbreaks of forest pests and pathogens [50]. Below, we review the major current and future threats to forest-carbon stocks.

Wildfire

The USFS identifies wildfire as a major disturbance for forest-carbon stocks for all regions and as the top-ranked disturbance for nearly all forestlands in the western Unites States [52]. Over the past decade, wildfires burned on average 2.8 million ha (7 million acres) per year. However, record fire years in 2015, 2017, and 2020 resulted in the loss of more than 4.05 million ha (10 million acres) to wildfire. From 2017 to 2021, wildfires emitted an estimated average of 140.8 million tonnes of CO_2 annually [9].

Wildfire size, duration, and intensity have all increased in the recent past and are expected to continue to increase in the future [53-55]. The last decadal rate of approximately 2.8 million ha per year lost to wildfire is 2.5 times higher than five decades ago [56]. Ensemble-model projections estimate that increasing annual average temperatures and decreasing precipitation and relative humidity will increase burned areas across the western United States by 24%–165% [55, 57, 58] with an estimate of ~50% increase in forest-fire emissions [59]. There is model convergence that these wildfires are more likely to be very large, stand-replacing fires [60]. High-intensity wildfires may lead to conversion of forestland to non-forested scrubland or grassland vegetation [61-64]; an estimated 6% of all western forests are at elevated risk of conversion to non-forest by mid-century [61]. Because the carbon density of forestlands is up to six-fold higher than in grasslands and shrublands [65], this wildfire-induced conversion represents a huge, potentially permanent, loss of terrestrial carbon storage.

Due to the high probability that most western forests will continue to be at extreme risk from large-scale, stand-replacing fires, promoting health- and fire-resilience-oriented management of these forests is a key opportunity for climate-mitigation benefits, which we explore in **Section 3.2**. Much more, it is also a way to protect communities and significant cultural, ecological, and spiritual assets within these forests.

BOX 2-3

Our Forests Face Challenges

Changing climates are increasing drought and wildfire events. The continued introduction and spread of new and old pests and pathogens, in conjunction with changing climates, are leading to larger and more frequent outbreaks of these organisms. Together, these disturbances are decreasing forest health and causing widespread tree death and declining rates of forest CO_2 removal. Some may argue that, because of these dire threats facing our forests, we should not invest funding or resources into forests as part of the Nation's climate-mitigation strategies. We propose three compelling reasons why forest management should be part of the CO_2 removal equation in the United States:

- Whether we choose to manage forests or not, forests are part of the global carbon-accounting budget. Right now, the Nation's carbon books benefit from forests as net carbon sinks. Declining forest health from these pressing and daunting climate-related disturbances reduces the capacity of forests to provide these carbon-sink services in the future. We can manage forests in ways that reduce the risks of widespread disturbances and increase the likelihood that our forests will be more resilient to these disturbances when they occur.
- Healthy forests can provide climate benefits beyond carbon capture and storage. Forest tree canopies cool air temperatures through tree canopy shading and releasing moisture into the air. Large tracts of forest also can control regional patterns of precipitation. When forest health declines, these additional non-carbon-based climate benefits also decline. Current carbon-accounting techniques do not estimate the magnitude of these non-carbon-based climate services of forests.
- Perhaps most importantly, our forests are not just DAC machines providing the single service of carbon capture and storage. Forests are vital for biodiversity; provide food, fuel, timber, and fiber; clean our air and water; and are of immense cultural, aesthetic, recreational, and spiritual value. When forests are cleared or unhealthy or when trees die from large-scale disturbances, human communities lose these services all at once.

For all these reasons, forest management is a central and complementary component to other CO_2-removal strategies. Additionally, most people manage forests for the variety of non-carbon-based benefits forests provide, meaning that forest management is never singular in focus. Managing forests for multiple services makes forest management an economically efficient CO_2-removal strategy. In our analysis, we do not downplay or ignore the large challenges that wildfire, drought, storms, and pests and pathogens create for managing forests. We do emphasize that the United States has a long history of forestry science that gives us the tools and knowledge to make scientifically founded decisions to mitigate and reduce the risks of these challenges.

Pests and Pathogens

Insects are ranked the fourth major disturbance to forest-carbon stocks for all USFS regions, and insects and disease are ranked in the top two threats for the northern and intermountain areas of the United States [52]. Large outbreaks of pests or pathogens can lead to high rates of tree mortality over wide expanses of forestlands [66]. A combination of climate change and introduction of non-native species has created pest- and pathogen-outbreak conditions in many forest regions [66, 67]. Recent USFS estimates suggest that approximately 5.3 million tonnes of carbon is lost each year to tree mortality from non-native insect pests, which are concentrated in eastern forests [29]. From 2006 to 2016, the average annual hardwood and softwood tree mortality rate increased by 38% and 34%, respectively [29].

Predicting exactly when or where pest and pathogen outbreaks are likely to occur in the future comes with high uncertainty [68, 69]. However, it is possible to identify regions at greater risk. The 2012 National Insect and Disease Risk Map identifies more than 71 million acres of forestland at risk of losing at least 25% of standing live basal area greater than 1-inch diameter between 2013 and 2027 [70]. Perhaps the only confident prediction about future forest pest and pathogen outbreaks is that they will continue to increase without concerted national policy efforts and adequate funding resources [67, 71, 72]. Improving international biosecurity policies and increasing biosurveillance activities can mitigate the risk of accidentally introducing new pests and pathogens in the United States or can increase chances of detecting them when (or before) they do enter [72, 73]. Declining forest health and tree death from pest and pathogen outbreaks leads to large economic losses in wood production, property values, and high costs of pest control [74]. Unsurprisingly, we can also document equally alarming losses in forest-carbon stocks from these causes [75, 76]. In **Section 3.3,** we explore how forest management can alleviate loss of forest carbon in the presence of pest and pathogen outbreaks.

Extreme Weather

The USFS identifies wind as the fifth leading disturbance to forest-carbon stocks for the southern United States [52]. Sustained extreme-weather events, like repeat drought years, can increase forest-tree susceptibility to mortality to other forest-health threats, such as pests and pathogens or wildfire [54]. Widespread or high-intensity extreme-weather events (e.g., hurricanes, tornadoes, windstorms) can lead to blowdowns of most canopy trees [77]. The southeastern Unites States has historically experienced the highest average tree mortality from hurricanes over the past century [78]. The average loss of forest carbon to hurricanes is 18.2 million tonnes of carbon each year with high variation depending on the number of hurricanes each year, the location of landfall, and the forest condition for each landfall event [78]. From 2006 to 2010, wind damage and drought disturbed an estimated 0.6 and 0.8 million ha each year, respectively, resulting in the loss of 6 ± 1 million tonnes of carbon each year in US forests [35]. Climate-change forecasts predict that extreme weather events, such as droughts, windstorms, ice storms, and floods, are likely to become more frequent, more severe, or both [79, 80].

Harvest

Approximately 2% of forestland each year is harvested for timber, and harvesting is the second leading disturbance to reductions in forest carbon in the Nation. Most harvested timber on US forestlands (89%) comes from private lands in the southern (58%), northern (15%), and Pacific Northwest (14%) administrative regions of the USFS [52]; **Figure 2-4**). While planned disturbances are a leading cause of forest-carbon-stock reductions, the total land base affected by harvest is smaller than the nearly 3% of forests that are disturbed by insects, disease, and fire. Additionally, some harvest practices may increase forest resilience to disturbances, promote healthier forests that can remove more CO_2 from the atmosphere, or increase the durability of forest-carbon stocks (**Section 2**). While forest harvesting removes carbon from the forestland base, a proportion of harvested timber goes into wood products that represent out-of-the-forest carbon-storage pools that vary in their duration [28]. For this reason, the US Inventory of GHGs reports carbon stored in wood products as part of the total forest-carbon pools and estimates that, in 2021, wood products stored approximately 102.8 million tonnes of CO_2e [9]

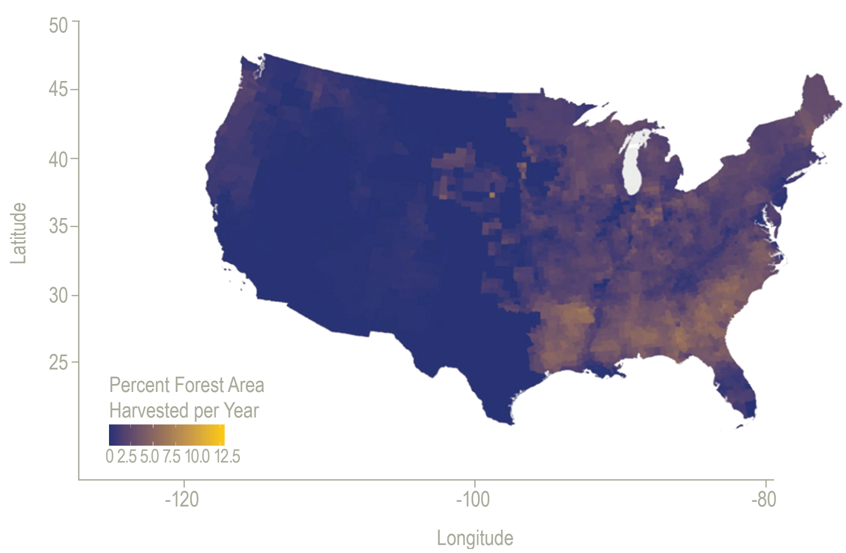


Figure 2-4. *Approximately 2% of forestland in the Nation is harvested each year. This map shows the proportion of the annual forest area harvested using the most recent US Forest Service (USFS) Forest Inventory and Analysis (FIA) national program, which uses the most recent inventory cycle for each state [29].*

2. Roads to Forest-Based CO_2 Removal

Forest management is an important pillar in climate-mitigation strategies. Sustainable management can simultaneously increase the forestland base, forest CO_2-removal rates, the durability of forest-carbon storage, and carbon storage in long-lived wood products. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report highlights that reforestation and improved forest management are among the few widely practiced CO_2-removal strategies that are technically viable and cost effective and provide additional benefits, including climate-change adaptation, biodiversity conservation, microclimatic regulation, soil-erosion protection, water and flood regulation, and local employment and improvement of local livelihoods [81]. Because many forest-management practices are technically viable today and scalable across the

United States, national estimates of forest climate-mitigation potential relative to other CO_2-removal pathways tend to be relatively low-cost and implementable in the near-term.

In this section, we review evidence from prior studies that have estimated how various forest-management practices could lead to increases in forest CO_2 removal and storage. We group these studies by the three primary levers that policymakers or forest managers may pull to increase future forest carbon outlined in Section 2.3: (1) increasing the total forestland of the United States, (2) increasing the rate at which forests remove CO_2 from the atmosphere, and (3) increasing the durability of forest-carbon storage.

2.1 Roads to Removal via Increasing the Forestland Area

Reforesting currently non-forested lands through active tree planting has one of the highest estimated potentials for forest-based carbon removal in the United States [5-7]. Multiple national assessments of US reforestation potentials support two key findings: (1) reforestation of agricultural lands on challenging soils provides a relatively low-cost opportunity for CO_2 removal and (2) a key region of high opportunity is the southeastern United States [4-7] (**Table 2-1**).

Planting trees on non-forested lands is not appropriate everywhere [82]. Converting habitats that would not include high tree densities without human intervention—including grasslands, shrublands, and many wetlands—would reduce the total area of these habitats, leading to declines in biodiversity and loss of services these ecosystems provide to humans [82]. Within the United States, however, the clearing of forestland in the 18th and 19th centuries converted historical forestland into what is today lands classified as agricultural lands (Box 2-2). Many of these agricultural lands exist on challenging soils for crop production, and these areas provide opportunities to expand the forestland base without compromising other biodiversity-rich grassland, shrubland, or wetland ecosystems. In **Section 3.1**, we assessed the reforestation potential of southeastern pinelands to estimate additional CO_2 removal and storage in new pine forests, as well as potential timber production and carbon-substitution benefits of building materials.

Table 2-1. *Despite wide divergence in findings, national studies show consistently strong agreement that increasing the United States' total forestland base through tree planting has high CO_2-removal potential.*

Study	Study Consideration	Area *(Million hectares)*	Removal Potential *(Million Tonnes CO_2/yr1)*	Cost	Key Regions of Opportunity
Cook-Patton et al., 2020 [4]	Restoring tree cover in former forest-land that is currently non-stocked forests, shrublands, protected areas, post-burn landscapes, pasture-lands, croplands with challenging soils, urban areas, floodplains, stream-sides, and biodiversity corridors	51.6	314.2	~50% at <$20 USD per tonne CO2e	Southeast United States (40%)
Fargione et al., 2018 [5]	Reforesting former forestland that is not currently wetland, active cropland, or livestock pastureland	62.9	306.6	~80% <$50 USD per tonne CO2e	Northeast (35%) and south central (31%) United States
Haight et al.,2020 [6]	Incentivizing private landowners in the eastern United States to plant trees on 12.1 million ha of marginal cropland, and planting trees in 3 million ha of federal forestlands in the western United States.	15.1	107	6.5 Billion	Southern United States (25-75 Tg CO2e/yr)
Wear and Coulston, 2015 [7]	Incentivizing private landowners in the eastern United States to plant trees on 2 million ha, and planting trees in federal forests in 3.7 million ha the wester United States.	7.73	27.6	–	Southern United States (1.48 tonnes ha-1 yr-1) and Pacific Northwest (1.10 tonnes ha-1 yr-1)

**While using similar tree planting approaches, Haight et al. 2020 and Wear and Coulston 2015 used different modeling approaches to estimate projected carbon gains.*

2.2 Roads to Removal via Increasing Forest CO_2-Removal Rates

A suite of forest-management practices can impact forest characteristics to increase the rate at which they remove CO_2 from the atmosphere. These practices can include planting or encouraging the establishment of naturally regenerating trees that are more resilient to disturbances or removing specific trees that release the remaining trees from competition (**See Appendix 2**). Forest management can influence the number of trees growing in an existing forest, the health of trees, the age and structure of forest stands and, with some limitations, the types of trees growing in a forest. However, there is limited empirical evidence to support assessments of the carbon impact of adopting these practices at the national level.

The most studied management option for forest-based climate mitigation is the extension of timber-harvest rotations on privately owned, commercial timberlands. Longer rotations keep large trees in the forest for longer, which protects existing carbon stocks, continues efficient CO_2 removal, and ultimately provides higher-value timber that could end up as wood products with longer carbon-storage potential. Deferred harvest of commercial timberlands also has risks. When foresters delay harvesting and hold timber "on the stump," they are forgoing that year's income and are risking that a natural disturbance that kills trees could reduce the value of their forestland. Additionally, deferred harvests of commercial timberlands may reduce the total supply of wood products reaching the market, which could lead to unintentional "leakage" when other forest owners are incentivized to harvest their forests to meet wood-product demand. Predicting the risk of leakage from deferred harvests is challenging and estimates of leakage risk are highly variable with plausible rates reaching 85% [83]. National estimates have found that deferred harvests of all non-plantation timberlands in the United States have a maximum mitigation potential of 267 million tonnes of CO_2e each year, with over 75% of this potential estimated to be less than $50/tonne of CO_2e [5, 84]. However, these estimates constrain near- and medium-term timber harvests on all commercial forestlands and are thus likely infeasible to implement immediately across all US timberlands because of the large annual consumption of wood products nationally and globally [29].

Opportunities also exist to increase the number of trees per area, or the stocking density of trees, within forestlands that would increase the total CO_2-removal rate of a given forest. Some forestlands, like dry western forests, are overstocked with too many trees (**see Section 3.2**). In other regions, forests are understocked, which means that planting more trees would add additional CO_2-removal capacity [8]. Recent estimates suggest there are 33 million ha (±0.47 million ha) of existing understocked forestland. If we planted trees within this existing forestland, we could potentially increase total forest CO_2-removal rates by ~20% of current removal rates, which would represent approximately 187.7 million tonnes of additional CO_2e removed annually [8]. Stimulating tree planting within existing forests will likely require economic incentives to cover planting and tree-maintenance costs [85]; tree planting and maintenance costs are estimated to be feasible at $50/tonne CO_2e [4].

2.3 Roads to Removal via Increasing the Durability of Carbon Storage

If we want to employ forests for their DAC capabilities, then it will be critical to properly maintain and protect forest storage "infrastructure." Forests store carbon within the forest—in trees, other vegetation, dead biomass, and the soil (**Box 2-4**)—and forest-wood products also store carbon outside the forest. Most international and national carbon accounting frameworks consider total forest-carbon stocks to be the sum of carbon stored within forest-carbon pools and wood products [9, 27, 81]. Forest management can increase the durability of total forest-carbon stocks by increasing the resiliency of forests to natural disturbances that lead to forest-carbon emissions and by creating wood products that store carbon.

Silvicultural practices—the art and science of managing forests for desired objectives—in the United States are philosophically different today relative to the past. Many new silvicultural practices incorporate ecological and non-economic values into management practices, as well as "adaptive" harvest practices designed to improve forest health and resilience to multiple forest disturbances [16, 86]. For example, thinning and reducing the total basal area of dry western forests may be one of the most important practices for protecting regional carbon stocks [10-12]. Forest-management policies that reduce fuel loads and forest tree density will reduce the probability of stand-replacing fires and large emissions from forest wildfires. In **Section 3.2**, we assess how fire-resilience thinning practices in dry forests can mitigate the severity of potential wildfires.

In other areas, adopting regionally appropriate silvicultural practices can protect forest-carbon stocks from large losses after natural disturbances, maintain supplies of wood products, and potentially provide economic incentives to

BOX 2-4

Forest Soils are Important Carbon Stores

The two major carbon stocks in most forests of the United States are the aboveground live tree biomass and soil organic matter (Figure 085). There is a rich body of knowledge that suggests that soil carbon stocks will be responsive to forest management, with the expectation that soil carbon stocks will increase under reforestation and with timber managements that retain live tree biomass and healthy, resilient forests. However, empirical support for these expectations is less conclusive. Studies report no change, pronounced losses or gains in mineral soil carbon stocks under forest management. Synthesis of this evidence leads to the conclusion that mineral soil carbon stocks do not, on average, respond appreciably to forest management. The default guidelines for national-level greenhouse gas accounting, issued by the Intergovernmental Panel on Climate Change, reflect these syntheses and assume no change in mineral soil carbon stocks for managed forestlands. Evidence syntheses published since those 2006 guidelines challenge this assumption, suggesting that conversion of primary forest to secondary forest, and both forest types to plantations, results in net soil carbon loss. Yet our assessment of the available evidence suggests that the paucity of empirical data on soil carbon stock responses should cast doubt on the validity of past syntheses.

Collection of new empirical data may reveal an untapped potential for management to remove atmospheric carbon dioxide into forest soils. These empirical data would need to be collected at higher densities than in past studies. Higher densities would more accurately enumerate stocks given high spatial variation in soil carbon stocks, which makes it difficult to separate changes in stocks due to management from measurement error. For this Report, forest soil carbon data were inadequate for making reliable estimates of soil carbon response to forest management, but these issues are addressable with investment in study and sampling design.

prevent the sale of unmanaged forestlands for commercial development [13-16]. Modern silvicultural practices have increasingly adopted regeneration practices that can emulate episodic natural disturbances and leave standing, mature trees. These regeneration practices can provide many benefits including keeping a local seed source for the next generation of trees, promoting a greater diversity of tree seedlings to recruit into the forest [87], and increasing both the overall age diversity of trees and the forest resilience to large disturbances (**See Appendix 2**). Regenerative practices may ultimately retain more carbon than unmanaged, evenly aged forests when forests are disturbed [13, 14]. In **Section 3.3** we assess how regenerative silviculture practices and common disturbances change the rates of CO_2 removal and storage capacity of forests in southern New England and New York.

Forest management also leads to production of wood products that store a portion of forest carbon and protect that carbon from future forest disturbances [9, 28]. Multiple novel and emerging technologies engineer harvested wood into longer-lived wood products used in building and construction materials, which have substitution benefits for more carbon-intensive products [88]. These technologies include engineered cross-laminated timber—that can replace building materials (e.g., concrete and steel) that have large carbon footprints—and wood biochar, which prevents the complete decay of wood carbon and may have additional carbon-capture benefits depending on its application [88, 89]. In **Section 3.1**, we focus on how planting new pine forests in the southeastern United States can generate additional timber volume that could be diverted to novel wood products.

3. Forest Management and Climate Mitigation

A key challenge of using natural ecosystems for CO_2 removal and storage is that there will always be events that alter climate and human behavior in complex ways that are hard to predict with even moderate confidence. While we may not be able to predict exactly when or where such an event will occur or what its effects will be, we can project how changes in human consumption or stochastic natural disturbances may change forest-carbon stocks or rates of CO_2 removal. We also note that, given different extents of knowledge and empirical data, confidence in the accuracy of the projected carbon benefits revealed by the case studies varies, with our greatest confidence in the southeastern case study (Section 3.1). As this is a prospective report, we do not spend time discussing how these projected rates of carbon removal can be measured and verified once management strategies are implemented. However, we do highlight that measuring impact is possible but would require investment to build confidence in the accuracy of estimated intervention effects (**Box 2-5**).

CO_2 removal is just one of the many services forests provide to humans. Forests also provide timber, fiber, fuel, jobs and economic opportunities in rural communities, habitat for biodiversity, non-carbon-based climate regulation, drinking water, air purification, recreational and educational opportunities, and cultural value [94]. These services have many synergies that forest management can optimize. In our analysis, we selected a few opportunities for three areas of the United States:

- Planting pine forests that support regional economies and provide less carbon-intensive building materials (see **Section 3.1**).
- Thinning fire-prone western forests to reduce wildfire hazards and carbon emissions (see **Section 3.2)**.
- Applying regeneration-focused harvests in southern New England and New York forests for wood products and increasing forest resilience to future natural disturbances (see **Section 3.3**).

BOX 2-5

Truth and Confidence in Forest Management as a Climate Solution

The idea that we cannot accurately bean-count every tonne of CO_2 removed from the atmosphere following forest management should not be a surprise. The true effect size of an intervention is unknowable and is an inherent feature of complex biophysical systems such as forests, just as it is with human populations. In public health, we develop policies and enact population-level interventions, such as vaccinations, in full knowledge that the true effect size is unknowable. Epidemiologists sub-sample the populations of interest and then estimate the mean, population-level benefit of the actions taken (e.g., how many more people per million individuals, on average, survive a disease). These studies do not predict whether any specific individual, if vaccinated, would survive following disease exposure. Science is not yet capable of such feats. Both economics and epidemiology show that we can confidently quantify the mean-effect size of an intervention at the collective scales at which they are applied in practice (i.e., to the population but not the individual). These so called "natural experiments" rely on careful integration of scientific knowledge, study design, and analysis of empirical data [95, 96].

When adopting natural experimental approaches, each unit (e.g., a forest stand) of forestland to which the management intervention is applied has similarities to an individual in a human population, possessing a unique history and context. These other factors mean that some forestland units will lose carbon while others gain carbon, independent of the intervention. Confidence in our ability to ascribe these changes to the management intervention should then be low at the individual-unit-scale. Yet, by using natural experimental approaches, it should be feasible to be reasonably confident in the accuracy of the estimated mean-effect size of the management intervention across the many thousands of units of forestland for the forest type under consideration. Despite calls for such empirical data collection to build confidence in forest-carbon solutions [97], natural experimental approaches to quantify CO_2-removal outcomes for working lands appear to be in their infancy (e.g., [93]) and represent a major opportunity to rapidly scale reliable quantification of natural climate solutions. Many carbon protocols focus instead on precision over accuracy of intervention effects, making them unable to differentiate between precisely right and precisely wrong effect sizes. Revising these protocols to focus on the accuracy of population-level estimates will ideally engender confidence both in forest-carbon.

3.1 Reforestation and Afforestation with Southeastern Pine Plantations

One of the most productive US forest regions is the Southeast. The temperate and moist climate of the region promotes faster tree growth and longer growing seasons, making this region home to some of the Nation's most carbon-rich forests. Southeastern forests are biodiverse and economically important with high potential for CO_2 removal through tree planting (Table 1). Here, we evaluate the CO_2-removal potential of planting loblolly pine (*Pinus taeda*) trees, a native and economically important tree in the region, across the southeastern Piedmont and Coastal Plains regions. We project the estimated carbon benefits of planting new pine forests for 100 years using a cradle-to-grave multiscale dynamic Life-Cycle Assessment (LCA) Framework. We adapted this case study from a published article [19].

We acknowledge that monoculture forests, including loblolly pine forests, are less biodiverse and more susceptible to pest and pathogen outbreaks than mixed-species forests [86], and most regional pine-forest restoration strategies focus on establishing the once-dominant longleaf pine ecosystems. Here we model pine restoration with loblolly pine to provide a directly comparable alternative to single-species pine plantations. Additionally, because most pine forests in the region comprise loblolly or other southern yellow pines, there are some efforts and existing knowledge on how to convert single-species pine plantations into more diverse, native long-leaf pine forests [98]. Planting and restoration efforts of native longleaf pine forests are also likely to provide substantial CO_2-removal benefits [99-103]. Planting new longleaf pine forests could also be considered part of a tree-planting strategy in the Southeast, especially for states, municipalities, or private landowners that have prioritized the restoration of this important habitat type [104].

Overview of Regional Forest Characteristics

As with much of the US forestland, the expanding population of European-American settlers deforested the vast majority of southeastern forests in the 19th and 20th centuries to build and heat homes in the region, build the new Nation's naval industry, and clear the land for agriculture and livestock [105, 106]. Unsustainable cotton and tobacco row-crop agricultural practices depleted soil nutrients and led to widespread erosion of topsoil. The widespread degradation of the southern Unites States' forests and soils led to widespread agricultural-land abandonment and launched the Nation's first major reforestation effort in in the 1920s by the USFS. During the 1930s, US Conservation Corp members planted more than 1.5 million acres of pine across the southern Unites States. These early efforts demonstrate that reforestation of degraded soils with pine plantations was effective and scalable, and led to increased research and development of pine seedling stock, plantation growth practices, and forestry operations [106].

Regional Forest Management for CO_2 Removal

There are two prominent and complementary forest CO_2-removal strategies for the southeastern United States: (1) creating new forestlands through loblolly pine reforestation and afforestation efforts and (2) converting harvested pine timber into long-term carbon-storage products [19]. These strategies leverage the region's warm temperate climate, the relatively fast growth of loblolly pine trees, and the economic opportunities of pine plantations to create scalable and relatively quick CO_2 removal [19, 107]. Large-scale pine-planting efforts have a history of success in the Southeast and have contributed to its moniker—the "wood basket" of the Nation. Today, pine forests are a vital component of the southeastern economy and are the Nation's most efficient means of producing wood products.

A sizeable amount of land—2.1 million ha—is available for tree planting today (**Figure 2-5**). This land is areas that were forested when European colonists arrived in North America in the 17th century. Today they are currently forests with sizeable canopy gaps or agricultural lands with challenging soils [4]. Notably, the land base best suited to pine reforestation has less than a 3% overlap with the land base suitable for switchgrass-biomass production (**Chapter 3 – Soils**) owing to key ecological and infrastructural differences in pine versus switchgrass establishment.

Expanding planted pine forests could encourage the development of nascent wood-product economies. Current plantations in the region supply harvested-wood products for traditional pulp and paper and sawlog mills [29]. Harvested timber and timber residues from new pine plantations could be diverted to innovative wood products, such as biochar and cross-laminated timber (CLT). Biochar is a carbon-rich product made by heating wood and can be used for bioenergy or could provide a more durable form of carbon storage when used as a soil amendment or pollution treatment [108, 109]. However, producing, transporting, and utilizing biochar all emit CO_2 and other GHGs, and the degradation rates of biochar when applied to soils are highly uncertain. Cross-laminated timber is an engineered timber that can be used as a stand-alone structural element in architecture and engineering and can substitute for more carbon-intensive

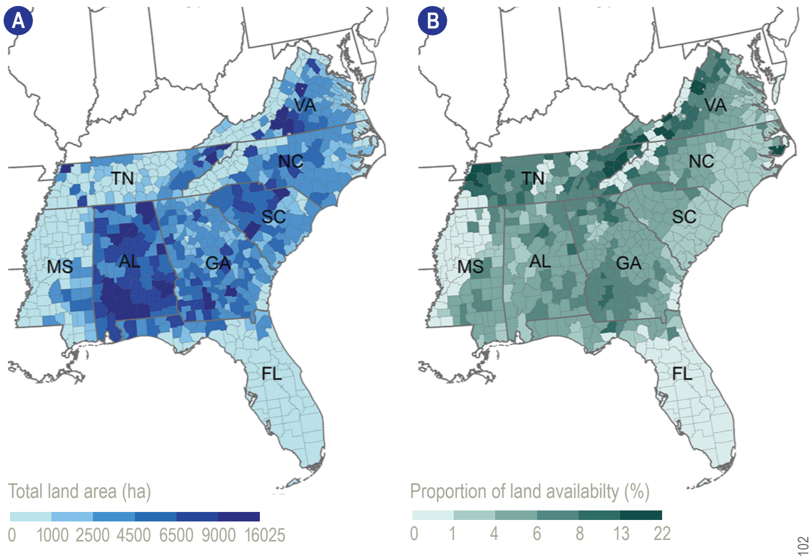


Figure 2-5. *The southeastern United States has approximately 2.1 million hectares (ha) of agricultural lands with challenging soils and non-stocked forest patches potentially available for pine planting. Maps depict the total land area in hectares available (A) and the aggregated proportion of land available (B) by county. Maps adapted from Zhang et al. (2023) [19].*

building materials, such as concrete and steel [110], and deliver >40% reductions in GHG emissions across the life-cycle of building construction [111]. However, improvements in processing CLT, efficiency of supply chains, and applicability in standards and building codes need to occur before we can realize the potential of CLT [112].

Two Roads to Removal via Planting New Pine Forests

Planting new southeastern forests with loblolly pine is one of the quickest ways to grow mature trees. Foresters can grow a mature, closed-canopy loblolly pine forest in 25 years, which would allow the Nation to reach near-term CO_2-removal potentials from additional, new forest creation by 2050. Importantly, because we are projecting carbon removal from new pine plantations, there would be no reduction in current pine-plantation land supplying pine for existing fiber, energy, or wood-product needs. This scenario likely avoids adverse harvest "leakage" impacts, which could lead to additional harvests of more biodiverse, non-commercial forests.

Substantial historic and contemporary research and development investments into loblolly-pine-plantation management make this strategy scalable and viable. The productivity and CO_2-removal potential of loblolly pine plantations have tripled over the past five decades owing to (1) advances in genetic breeding of pine-seedling stock, soil preparation, and fertilization practices that improve soil conditions for tree growth and (2) adaptive vegetation management and silvicultural practices that reduce competition and stimulate growth [106, 107, 113]. Additionally, forest managers have collected extensive pine-forest inventory and growth datasets that measure tree response to site conditions and management practices [106, 107], and forest modelers have developed pine-specific modeling tools for projecting planted loblolly pine growth under a broad array of site conditions [114]. These empirical datasets and modeling tools make it possible to project total planted pine-forest carbon gain in response to climate, soil conditions, and management interventions across a broad geographic region.

We analyzed the carbon benefits of planting loblolly pine trees, at two planting densities, across 2.1 million ha of land that are currently forested with sizeable canopy gaps or agricultural lands with challenging soils. For all projections, we assumed that planting efforts begin in 2025 and that the aboveground and soil-carbon stocks in unplanted lands are zero and current state, respectively [19]. After planting pines, we estimated the total CO_2-removal potential for two viable, but distinct, forest-management options: commercial pine plantations or pine-forest restoration (**Figure 2-6**).

Commercial Pine Plantations

Forest managers may opt for a "commercial plantation" strategy, which would include typical plantation-management practices that optimize wood-volume production. Under this management strategy, plantations would grow more total trees through time on the same land base, but carbon gains would only be realized if net emissions from commercial forestry practices were lower than the net carbon-storage gains in forests and harvested wood products

Current pine-plantation management has carbon costs. Typical plantation management includes operating machinery and applying synthetic fertilizers that lead to GHG emissions. The initial planting density of pine seedlings can also impact total carbon costs or gains. Managers may plant pine seedlings at high densities, which requires higher fertilization rates and a "precommercial thin" to remove excess planted

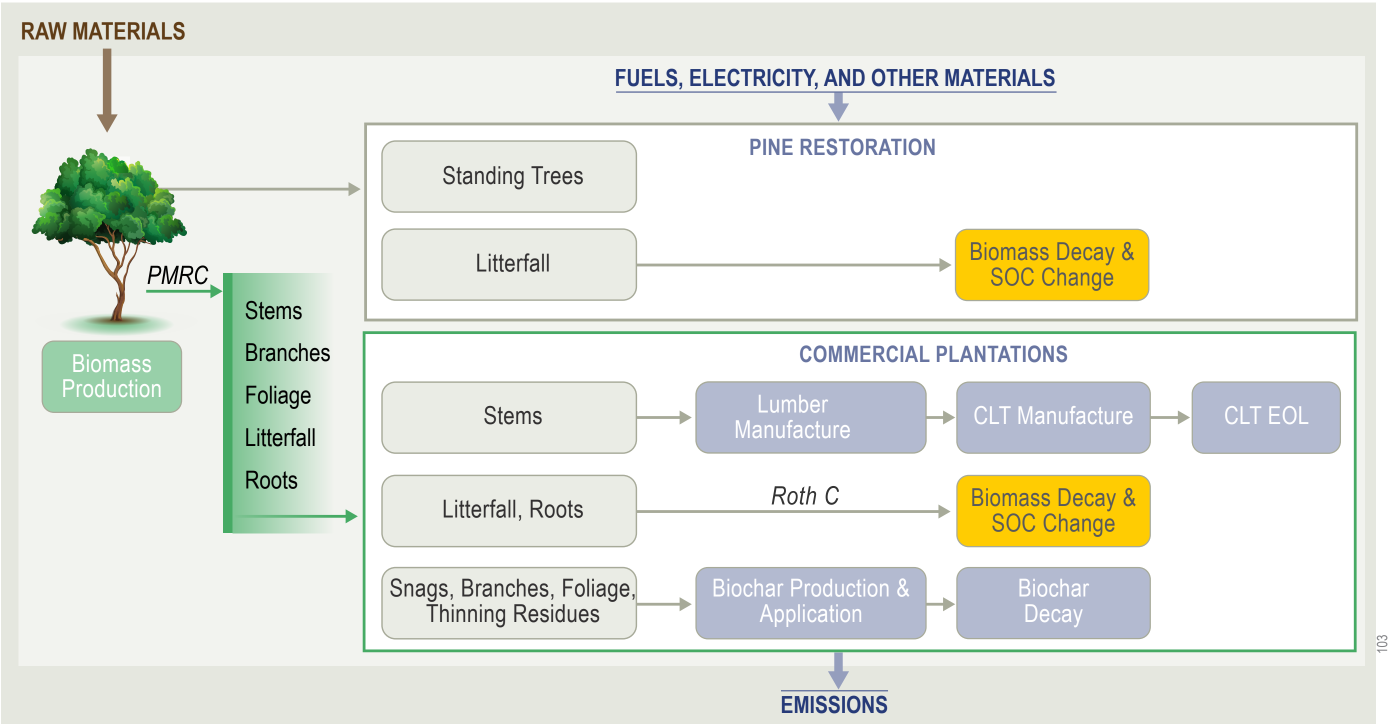


Figure 2-6. *We estimated the projected CO_2-removal and -storage benefits of loblolly pine reforestation and afforestation using a life-cycle assessment (LCA) framework for two forest-management options: "pine restoration," which optimizes carbon storage in living forest trees and soil organic carbon (SOC) pools, and "commercial plantations," which optimizes carbon storage in novel wood products, such as biochar and cross-laminated timber (CLT). To model pine-tree growth in both scenarios, we used the Plantation Management Research Cooperative (PMRC) whole-stand growth and yield model, and to model soil carbon, we use the RothC SOC model. This LCA framework accounts for greenhouse gas (GHG) emissions from commercial-plantation forestry operations, wood-product and biochar production, and decay and end-of-life (EOL) for novel wood products*

trees. If managers plant at lower densities, they can reduce total fertilizer application and avoid precommercial thinning, which can reduce total GHG emissions. We projected the carbon gains from planting trees at low (450 trees/acre) and high (900 trees/acre) seedling densities. To project the estimated amount of CO_2 sequestered and stored in forest vegetation and soils, we used the 1996 Plantation Management Research Cooperative whole-stand growth and yield model [114, 115] and the RothC Soil Carbon Model [116], respectively (Figure 103).

We added a multiscale LCA framework to account for all GHG emissions that arise from forestry operation, transportation, and manufacturing; use of biochar and CLT products; and decay of products at the end of their life, as well as climate substitution benefits from CLT use (Figure 103). We created biochar from the small trees removed during the precommercial thinning harvest and additional "timber residues"—which includes the lateral branches, stems, foliage, and tree tops—from harvested whole trees. We removed 50% of residues and left the remaining residues on site, which we note is larger than most pine-plantation operations. We assumed all whole trees harvested would go to CLT. We accounted for uncertainty by modeling optimistic, average, and pessimistic climate, growth conditions, and soil and wood carbon content within the LCA framework. Optimistic conditions included moderately cooler and drier future climate conditions; soil conditions with higher clay content , which optimizes carbon storage in the forest soil-carbon pool; faster and larger tree growth; and the maximum carbon-substitution benefits for CLT. Pessimistic conditions explored the opposite bounds of each of these conditions. We assumed that these extreme conditions represent the bounds of projection uncertainty. In all estimates, we reported the total carbon or GHG gains based on average model conditions and reported optimistic and pessimistic conditions as the upper and lower bounds of all estimates, respectively. See Zhang et al. (2023) [19] for full details on all analyses.

Pine Forest Restoration

Alternatively, after planting pine trees, forest managers may opt for a "pine restoration" management strategy that prioritizes carbon storage in forest vegetation and soils. Under this strategy, managers would not harvest planted trees and would allow a closed-canopy pine forest to remain on the land.

Pine Afforestation and Reforestation CO_2-Removal Potential by 2050

Assuming initial planting of all forests in 2025, reforesting 2.1 million ha of land in the southeastern United States could remove between 1.51 (1.18–1.90) and 1.78 [1.39–2.23] billion tonnes of CO_2e by 2050 depending on the forest-management strategy and the initial pine seedling planting density (**Figure 2-7**). Although CO_2-removal rates of forests are non-linear through time, dividing theses values by the 25 years of forest growth gives a linear annualized rate of between ~60.4 and 71.2 million tonnes of CO_2e per year by 2050.

Pine-Restoration Carbon Stocks after 25 Years

In shorter timeframes (less than 50 years), pine-restoration forest management is likely to yield higher total GHG mitigation potential than commercial-plantation management under "average" environmental conditions, with greater short-term benefits from initially planting pine seedlings at high densities of 900 seedlings per hectare (Figure 104). This outcome is a result of fast forest growth in early years with no loss of forest carbon to timber-harvest removals (Figure 4.2d). After 25 years of pine restoration, nearly all carbon gains in pine-restoration forests come from increases in living pine-tree biomass with minimal accrual of carbon in forest soil organic carbon (SOC) pools **(Figure 2-8**). High-density seedling planting yields slightly higher total forest-carbon stocks of 0.49 (0.38–0.61) billion tonnes of carbon compared to low-density seedling planting of 0.41 (0.32–0.52) billion tonnes of carbon after 25 years. However, total GHG-mitigation potential varies depending on the forecasted environmental conditions, which we discuss later in this section.

Commercial-Plantation Carbon Stocks after 25 Years

While pine-restoration management optimizes carbon stored in forest vegetation, commercial-plantation management optimizes carbon stored in novel wood products, such as CLT and biochar, as well as in SOC pools (Figure 105). Interestingly, RothC SOC-projection models estimate that SOC pools would increase approximately 10 fold under commercial-plantation management (105 and 140 million tonnes of carbon for low- and high-density planting, respectively, after 25 years) relative to pine-restoration management (~12 million tonnes of carbon after 25 years). This large increase in the SOC pool is a function of adding timber residues to plantation-forest soils after thinning and final-harvesting operations. High-density seedling planting within a precommercial thinning treatment yields slightly higher total carbon stocks after 25 years than low-density seedling planting: 0.44 (0.34–0.55) versus 0.40 (0.35–0.56) billion tonnes of carbon, respectively (Figure 105).

Pine Afforestation and Reforestation CO_2-Removal Potential by 2125

Assuming initial planting of all forests occurs in 2025, reforesting 2.1 million ha of land in the southeastern United States could deliver up to approximately 4 billion tonnes of GHG mitigation by 2125. In longer time frames, managing planted pine forests as commercial plantations and diverting harvested-wood products for biochar production and CLT delivers more total GHG-mitigation potential than managing planted pine forests for restoration: 4.08 (2.76–5.78) versus 3.69 (2.87–4.61) billion tonnes of CO_2e over 100 years (Figure 104). Planting pine forests for commercial production at lower densities has slight long-term benefits over planting at higher initial densities (total CO_2-removal benefit of 4.04 (2.62–5.88) billion tonnes of CO_2e).

The longer-term CO_2-removal potential of commercial plantations arises for two primary reasons. First, commercial-plantation management harvests and replants new pine trees every 25 years to maintain timber-product output, which keeps forest-growth rates stable between each 25-year harvest cycle. Conversely, the growth rate of forest carbon in pine forests managed for forest restoration decreases through time, as maturing trees age and total forest-growth rates slow (Figure 105). Second, when commercial-plantation forestry diverts wood products into durable and long-lived carbon-storage pools, such as biochar and CLT, the carbon value of these pools grows through time. The carbon-substitution benefits of CLT replacing more carbon-intensive building products, such as steel and concrete, account for 11% of the total GHG-mitigation potential of commercial-pine-plantation management strategies.

Estimated Costs and Benefits of Pine Planting for CO_2 Removal

We estimated the net costs of planting pines and managing commercial pine plantations, as well as potential income from sale of timber. Our cost methods estimate costs from the perspective of a private landowner—the dominant type of forestland owner in the region (Figure 086)—investing in pine planting for restoration or commercial-plantation purposes. A landowner may be motivated to cover initial planting costs through tax incentives or economic subsidies (or "payment for practice" subsidies) or may be motivated to pay up-front management costs for later revenues through the sale of

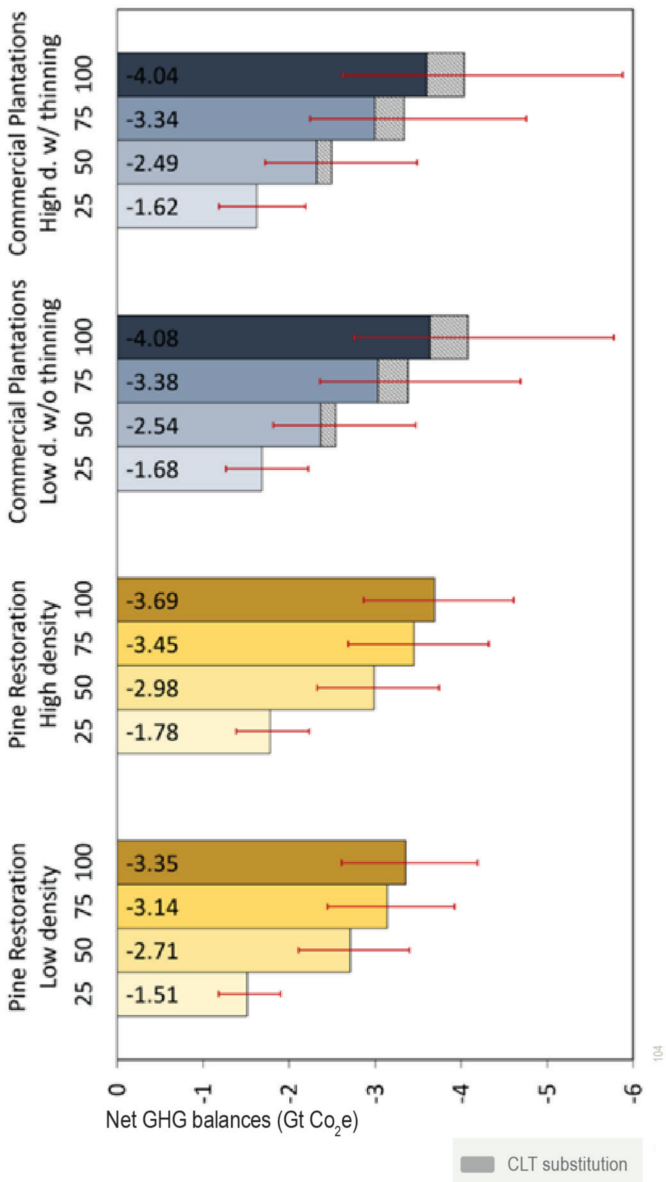


Figure 2-7 *Planting loblolly pine trees on 2.1 million hectares (ha) of land in the southeastern United States could likely remove ~1.5 billion tonnes of CO_2e (Gt CO_2e) from the atmosphere after 25 years and up to 4 Gt CO_2e from the atmosphere after 100 years. Forest managers can achieve these short- and long-term CO_2-removal potentials by managing planted pine forests for pine-forest restoration only (no timber harvests) or for commercial-plantation timber production for novel wood products (biochar and cross-laminated timber (CLT)), with low or high initial pine-seedling plant densities or with precommercial thinning operations. Error bars represent projected emissions under pessimistic and optimistic environmental conditions, and mean values represent projected emissions under average conditions. Net greenhouse gas (GHG) balances include cradle-to-grave GHG emissions from all forestry-management operations; tree growth and carbon gains and emissions from the soil; durable wood product and biochar manufacturing; decay of products at the end of their lives; and substitution benefits from CLT use. We estimated net GHG balances at 25-year intervals from initial tree planting; thus, if planting commenced in 2025, these bars would represent net GHG balances at 2050, 2075, 2100, and 2125 respectively.*

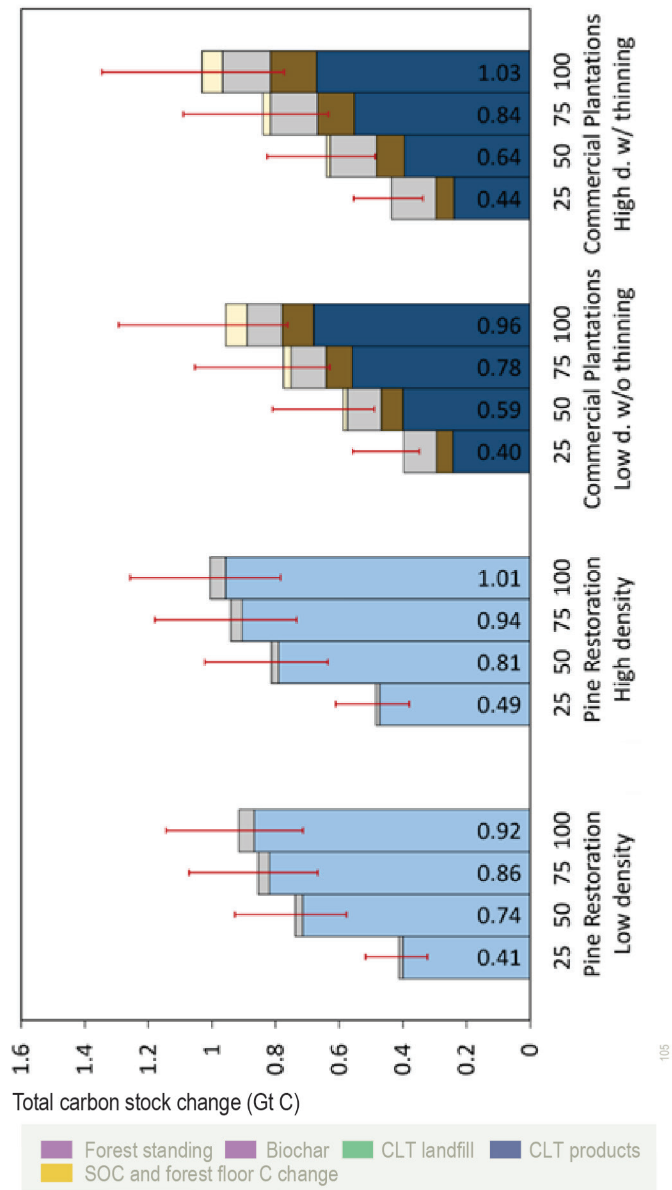


Figure 2-8. *Different management strategies after planting loblolly pine trees on 2.1 million hectares (ha) of land could accrue similar total carbon-stock increases of ~1 billion tonnes carbon (Gt C) over 100 years but in very different storage pools. Managing planted pine forests for forest restoration increases carbon storage in living forest vegetation and forest soil organic carbon (SOC), while managing planted pine forests for commercial plantations for novel wood products increases carbon stored in biochar, cross-laminated timber (CLT), and forest SOC through the increased addition of forest-harvesting residues. We modeled total carbon-stock changes using a cradle-to-grave life-cycle assessment (LCA) framework (see Figure 103) and estimated total carbon-pool size at 25-year intervals. If planting commenced in 2025, these bars would represent carbon stocks at 2050, 2075, 2100, and 2125, respectively.*

timber. Our cost estimates differed in approach from methods used in **Chapter 6 – BiCRS**, which assumed the perspective of a sawmill purchasing harvested material to produce wood products.

For pine restoration, we accounted for the initial establishment costs of prepping planting sites and planting pine seedlings following model assumptions **(Appendix 2** and [19]) and using regional average cost values [117], [118]. Total establishment costs are $784/ha for low seedling-density planting (450 seedlings per ha) and $1034/ha for high seedling-density planting (900 seedlings per ha).

Management of commercial plantations will incur the same initial establishment costs as management for pine restoration but will also have additional costs of managing trees to maximize commercial value and revenues from the sale of pine timber [117]. Additional management costs include application of fertilizer ($217/ha) and pre-commercial thinning ($356/ha). To estimate revenue at final harvest, we estimated the price a logger would pay a landowner (the "stumpage price") for southern pine at $28.51/tonne of green biomass [119]. Altogether, for each 25-year rotation, commercial plantations incur average costs of $1001 and $1607/ha and receive average stumpage sale revenue of $12,054 and $11,897/ha, under low-density planting without pre-commercial thinning and high-density planting with pre-commercial thinning, respectively. This leads to net economic benefits of $11,053 and $10,290/ha, respectively.

After 25 years (by 2050) under "average" environmental conditions, pine restoration with high-density planting provides the highest annualized CO_2 removal—71.14 million tonnes of CO_2e each year—at $1.22/tonne of CO_2e (**Figure 2-9**). Commercial plantations provide slightly lower CO_2-removal rates at 67.27 and 64.87 million tonnes of CO_2e per year under low and high planting density, respectively, which is higher than the 60.45 million tonnes of CO_2e removed per year from pine restoration with low-density planting. Commercial plantations also provide net economic benefits at around $13.50/tonne CO_2e removed.

After 100 years (by 2125), commercial plantations remove an average of 40.79 and 40.38 million tonnes of CO_2e each year with low- and high-density planting, respectively. Their net economic benefits—approximately $22/tonne CO_2e removal—almost doubled that of commercial plantations in 2050, despite the reoccurring establishment and management costs. Pine restoration with low- and high-density planting removes 33.55 and 36.87 million tonnes CO_2e per year, respectively, which is lower than that removed by commercial plantations due to the absence of carbon storage and substitution by CLT and biochar. However, this CO_2 removal comes with an extremely low price—approximately $0.54/tonne CO_2e.

High CO_2-Removal Potential No Matter How You Manage Newly Planted Pine Forests

All model projections demonstrated large positive short- and long-term CO_2-removal potential through pine planting efforts in the southeastern United States, regardless of whether planted pine forests were managed for pine-forest restoration or for commercial plantations and novel wood products (Figure 104, 105). These carbon benefits come at very low initial investment costs ranging from $0.60 to $2.20/tonne CO_2e. This finding is good news and suggests that pine-reforestation efforts would be robust under a wide range of circumstances and that carbon gains to forest or wood-product carbon pools would be "additional" to current land-management strategies.

However, there is not a single management strategy that would lead to the highest CO_2-removal potential across time, space, or future environmental conditions (**Figure 2-10**). In other words, while pine planting in the region is likely a strategy that will lead to net carbon benefits if implemented in 2025, the "optimal" management strategy of these forests will vary depending on the time horizon a policymaker wishes to emphasize, the specific location and growing conditions of the newly planted pine forests, and the future environmental conditions. The optimism or pessimism of future environmental conditions also affects which forest-management scenario and planting density has the highest potential carbon benefits. For example, under optimistic conditions, managing planted pine forests for commercial plantations and novel wood products has higher total CO_2-removal benefits after 100 years than managing planted pine forests for restoration, but under pessimistic conditions, the two management strategies are nearly equivalent (Figure 104). Note that we did not incorporate how uncertainty in stochastic and unpredictable environmental disturbances—such as insects, disease, wind, and fire—effects carbon stocks or CO_2-removal potential.

A large-scale pine-reforestation campaign across the southeastern United States has substantial CO_2-removal potential, with the added benefits of increasing the total forestlands and forest connectivity in the region and the potential to increase forestry-related jobs and local economies and to provide additional wood resources with high carbon-substitution values. Thanks to historic investments in research and development of loblolly pine forestry and successful historic reforestation campaigns, this strategy is likely achievable and scalable.

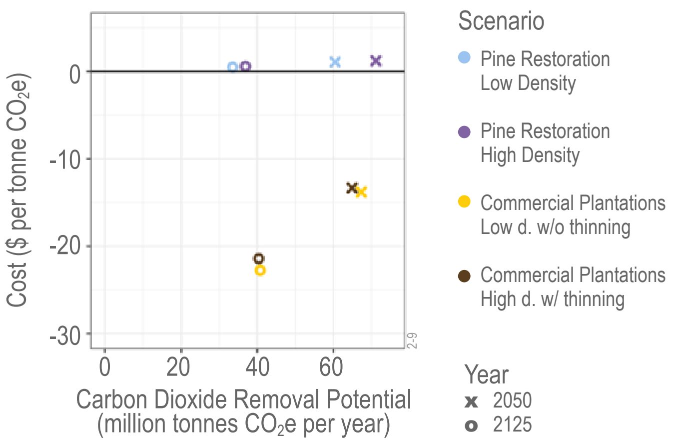


Figure 2-9. *Estimated cost-supply for planting loblolly pine trees across 2.1 million hectares (ha) in the southeastern United States. Forest managers may manage planted pine forests for pine-forest restoration only (no timber harvests) or commercial-plantation timber production for novel wood products (biochar and cross-laminated timber (CLT)), with low or high initial pine-seedling plant densities or with precommercial thinning operations. If all hectares of land are initially planted in 2025, we estimate costs for the year 2050 (25 years after planting) and 2125 (100 years after planting). Costs are the net balance of establishment costs, timber-management costs, and revenue from sale of pine timber harvested at 25-year intervals. Negative costs therefore represent net earnings.*

3.2 Fire-Resilience Treatment of Western Dry Forests in the Wildland-Urban Interface

This case study considers carbon management in dry, fire-prone forests of the western conterminous United States. For many western forests, past logging, lower grazing pressures, wetter climates, and fire exclusion have led to a high density of smaller trees that compete for limited light, water, and growing space. These challenges coupled with a climate that is warming and drying, a landscape facing more frequent and severe outbreaks of native forest-insect pests, and the invasion of non-native grasses that increase total flammable vegetation, these dense forests are under greater environmental stress than their historical reference. The current condition of these dry, fire-prone forests puts them at high risk of severe disturbance and large CO_2 emissions from wildfire and pest and pathogen outbreaks.

Given the current condition of dry western forests and the likelihood of future wildfires, forest managers could focus on applying management treatments that reduce the likelihood of catastrophic fires—and of losing forest carbon to these fires. This goal has the immense benefit of not only protecting forests themselves from catastrophic fire but also of protecting the residential, recreational, historic, hydrological,

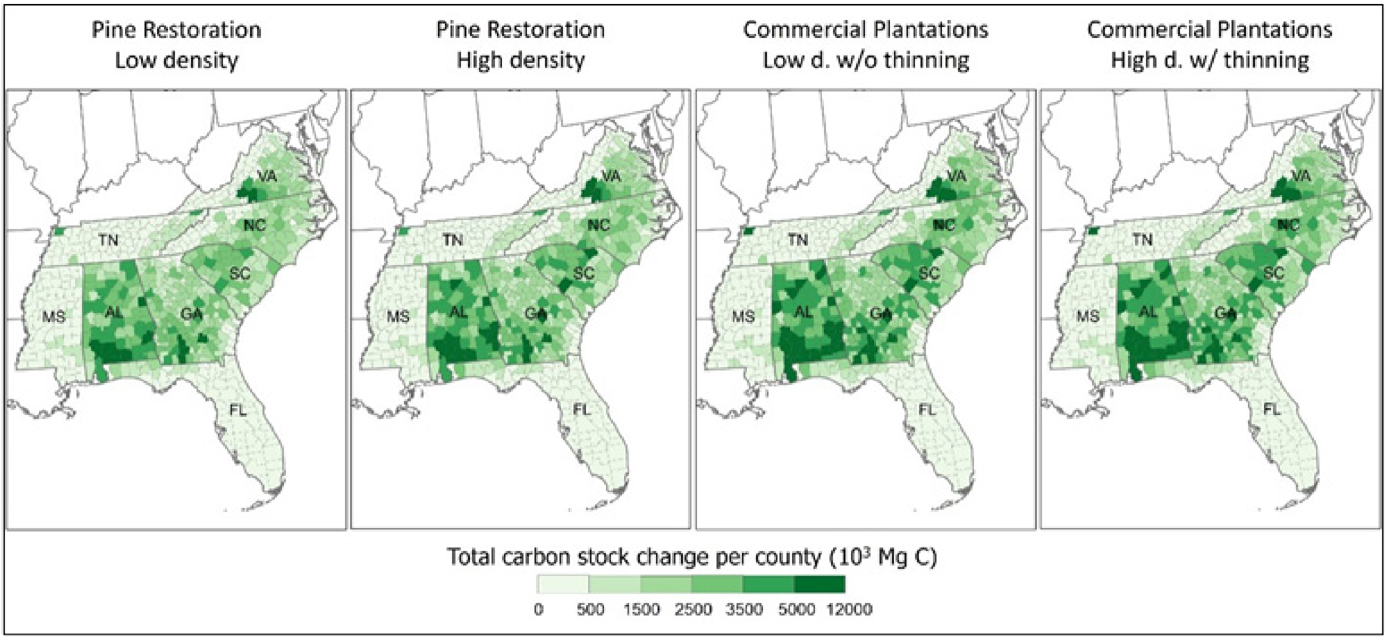


Figure 2-10. *Planting loblolly pine trees on 2.1 million hectares (ha) of land across the southeastern United States could increase total forest-carbon stocks across all counties over 100 years. However, the total change in forest-carbon stock varies by county based on land area available and forest-management decisions after planting. Forest managers may manage forests for pine restoration only (no timber harvests) or for commercial-plantation timber production for novel wood products (biochar and cross-laminated timber (CLT)), with low or high initial pine-seedling plant densities or with precommercial thinning operations. Positive values and darker green colors indicate carbon-stock increases from pine planting.*

spiritual, cultural, and ecological resources that are near and among and part of these forests. While these fire-resilience management treatments include removing trees and vegetation through cutting or burning—which leads to CO_2 emissions in the near-term—they are more likely to reduce overall CO_2 losses when wildfires occur in the future.

In this case study, we modeled the carbon impacts of treating fire-prone forests to make them more resilient against wildfire—reducing the likelihood of catastrophic, stand-replacing fire. We considered only forests that are next to (or surround) human communities and their structures—forests within the "wildland-urban interface." We chose to model this subset of western forests because it was a reasonable scope given the constraints of our time, resources, and modeling environment. Actual fire-resilience treatments would not—and should not—be constrained to the wildland-urban interface; rather, treatments should target the broader forest landscape and be implemented where they are most beneficial to as many resources as possible.

We found that many (but not all) of the forests we considered have the potential to store more carbon under conditions of active fire-resilience management compared to no management. We also considered the complexity and diversity of these forests—and thus the need for local forest knowledge and expertise—and the role of forest biomass utilization in reducing forest-carbon losses to wildfires.

Overview of Regional Forest Characteristics

We considered fire-prone forests within the USFS administrative regions 1–6, which include the forests within Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oregon, South Dakota, Utah, Washington, and Wyoming (**Figure 2-11**). We focused on USFS regions 1-6 because most western forests are public forests (69%), and most of these public forests are national forests (68%; [120]). Thus, the USFS will continue to lead on implementing climate-beneficial forest practices in dry western forests.

Though coastal areas in the Pacific Northwest support high-moisture-dependent species groups, such as the Hemlock-Sitka Spruce Group and Redwood Group, the majority of forest area in the region is composed of species that are adapted to—or have adapted under—dry conditions, frequent fire, and/or high elevation, such as the Ponderosa Pine, Pinyon-Juniper, Western Oak, California Mixed Conifer, or Douglas-Fir Group [121]. Note that Pinyon-Juniper is maladapted to fire but now is fire-prone because of human modifications of the landscape and invasive grasses. Collectively, we refer to these diverse forest-type groups as "western dry forests." We acknowledge the diversity of forest types in the region—and within these groups themselves—but for this study, we focus on these species groups because of their shared susceptibility to increasingly prevalent catastrophic fire.

The current vertical structure, spatial distribution, and species composition of western dry forests is largely the result of changes in land use following the violent displacement of Indigenous communities by settler colonists. Indigenous forest stewards intentionally introduced fire and also allowed western forests to experience more frequent, lower-severity fires initiated from lightning strikes [122]. This led to forests with fewer, larger trees that were more resilient to pests, pathogens, and fire. Colonial expansion displaced Indigenous communities, reduced forest-fire activity, converted forests to grazing lands for livestock, and extensively logged forests for railroad and home construction [123]. Relative to their historical reference, these logged forests regrew with a higher density of small, young trees [124, 125] and are organized in a more homogenous structure [124-127].

Our historic forest-management decisions have created western forests that are full of high-density, smaller trees that are now experiencing warmer and drier conditions than in the past. Additionally, federal and state forest-management policies have actively excluded fire from our forests for more than a century, continuing the trend of fire suppression that has increased flammable-vegetative-fuel loads [127]. Altogether, today's western forests are burning across larger areas and at higher severity than the historical, low-severity fires used by Indigenous forest stewards [53, 54]. Some of these high-severity fires are converting forests to open

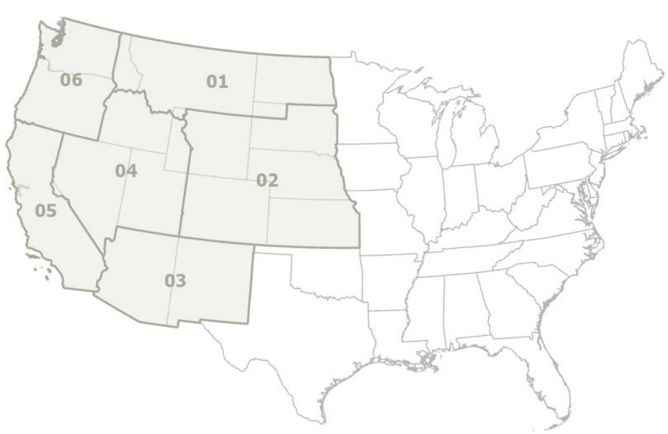


Figure 2-11. *Map of the six US Forest Service (USFS) administrative regions included in our analysis of the carbon-storage benefits of managing dry forests for fire resilience. Within these regions, we projected the carbon-storage benefits of managing forests near human communities and structures (the wildland-urban interface).*

shrubland or grassland ecosystems with reduced carbon-storage capacity [63]. Further, regional climate trends are expected to become hotter and drier in the future, likely increasing the area and severity of wildfires to an even greater degree in the near future [128].

High-severity forest fires threaten not only the forests, but also the myriad of valuable resources these forests provide. In recognition of this threat, many federal, state, and local agencies continue to foster fire-resilient forests. The 2014 interagency National Cohesive Wildland Fire Management Strategy gave strategic direction to wildfire planning [129]. The USFS outlined their approach in 2022 in Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America's Forests [130]. The Inflation Reduction Act committed an additional $1.8 billion to projects reducing hazardous fuels [131]. Most efforts go toward protecting residential communities that are at risk from severe forest fires—communities within the wildland-urban interface. Continued interest in promoting fire-resilient forests and protecting people living near and within the wildland-urban interface of western dry forests motivates our analysis.

Regional Forest Management to Reduce CO_2 Emissions

Dry western forests are carbon sources, not carbon sinks. In 2019, the US Inventory of GHGs estimated that the forests in 10 western states—all of which are considered in this case study—emitted more CO_2 to the atmosphere than they removed (Figure 087). These CO_2 emissions are a direct result of wildfires, which burn and release CO_2—as well as other potent GHGs, such as methane and nitrous dioxide [132]—to the atmosphere, which would otherwise be stored in living forest vegetation, dead wood, and organic matter at the soil surface.

The best tool for storing more carbon in dry western forests is to reduce fuel loads—both on the forest floor and in total tree volume—to foster fire-resilient forests. How a forest responds to a wildfire depends on the age, size, density, and spatial distribution of the trees in that forest; the amount of combustible material on the forest floor; and the local climate and weather conditions at the fire outset. A forest manager cannot control some of these conditions. If there has been limited precipitation and high temperatures, forest soils and plant tissues will have low moisture levels and be more likely to burn. If a fire starts on a windy day, it will spread faster than if the air is still. However, there are some conditions that a forest manager can control. By managing the density of trees and the total fuel load in western dry forests, forest managers can reduce the probability of a high severity wildfire.

When forests have a lower density of trees and lower amount of fuel, fires will likely be of a lower severity, will have lower heat intensity, and will tend to only burn the vegetation found on the forest floor. As a result, low-intensity wildfires tend to kill only smaller trees and shrubs and to thereby reduce resource competition for the remaining larger trees. When forests have a higher density of trees—like the condition of many of our dry forests in the western United States today [133]—they are more prone to high-severity fires. These fires burn at higher heat intensities than low-severity fires and tend to burn not only ground vegetation, but also the tree canopies, reached via ladder fuels [134].

Our best method to reduce fuel loads—and thus foster healthier forests that lose less CO_2 to wildfire—is a combination of thinning and intentional burning [10-12]. "Thinning" in forestry is any management treatment that is focused upon the benefit of the remaining trees [135]. In fire-prone forests, we tend to favor older, larger trees, aiming to benefit them by reducing competition for resources from smaller, younger nearby trees and removing ladder fuels that could allow a ground fire to reach the larger trees' canopies. For these reasons, we conduct "restoration thinnings" or "thinnings from below": removing small trees first. We should also note—though we could not address this with our modeling approach—the spatial composition of trees within a forest plays a crucial role in fire resilience; specifically, spatial heterogeneity (more gaps and clumps) is better than homogeneity (a uniform structure) [126].

Pile burning is a way to reduce the fuel load within a forest. Small, non-merchantable residues of trees—or slash—that are left after a mechanical treatment are gathered into a pile. That pile is then burned when conditions are favorable: high-moisture conditions in the fuel and atmosphere that make the unwanted spread of fire incredibly unlikely, along with atmospheric conditions that disperse smoke in a manner that does the least damage to the health of nearby communities. Pile burning is fueled with small trees, brush, and other vegetation that currently has little to no economic value. As a result, the amount of vegetation that gets pile burned—rather than stored in wood products—is greatly influenced by the local wood-product market. A de-emphasis of timber production in western national forests has led to a decline in sawmills near dry western forests [136]. The limited number of sawmills in the region means that most forests are too far from mills to transport any timber, increasing the costs of removing any thinned trees and increasing the likelihood that pile burning is the only option for reducing fuel load.

Investing in technology and infrastructure of sawmills or lumber-production facilities that require/can use small-diameter wood products—such as glue-laminated timber or CLT, biochar, or biomass-to-energy (see Chapter 6 – BiCRS)—would create jobs that lead to improved carbon sequestration. Using these small-diameter wood products would not only reduce their direct emissions to the atmosphere, but could also provide beneficial substitution effects when used in lieu of high-emission products, such as concrete and steel for buildings or coal for energy.

A key challenge in managing forests for fire resilience is determining the appropriate target structure of a given forest, including the density of remaining trees, distribution of sizes, and the spatial relation between one another (**Box 2-6**). While it is well-accepted that reducing current tree densities in forests fosters fire resilience, determining the optimal stand density for a forest is challenging. Specifically, we lack data on the structure and density of forests before Euro-American disruption, and it is a difficult experimental context: manipulating forest conditions is expensive to do, and we cannot ethically create a catastrophic fire within these test conditions to see how they respond. Continuing to develop knowledge around the effects of different fire-resilience treatment targets will be critical for helping local forest stewards manage forests for health and resilience in the face of our changing climate.

Identifying Fire-Prone Forests that Pose a Risk to Communities

We identified 479,799 ha (1,185,609 acres) of fire-prone forests that are within the wildland-urban interface (defined here as both intermix—communities among vegetation—and interface—communities within 2.4 km of large vegetation patches) and thus pose a potential wildfire risk to neighboring communities. We modeled management within fire-prone forests of the wildland-urban interface as it is a consistent, feasible management objective throughout the considered region. We note that although the wildland-urban interface is defensible for our large-extent model, not all treatments fall exclusively within the wildland-urban interface nor should they. Local experts and communities must guide where we treat forests, and the wildland-urban interface will not always be the best option [137].

To identify forested regions within the wildland-urban interface that are at the highest risk of wildfire, we used the spatial intersection of multiple high-resolution mapping resources. First, we used TreeMap 2016 [138]—a 30-m × 30-m raster data product in which each pixel's value is matched to the most similar USFS Forest Inventory and Analysis (FIA) plot number—as the basis for our analysis. We used the map by Carlson et al. (2022) [139] to set TreeMap to consider only those pixels that fall within the wildland-urban interface. We included forests in both interface and intermix areas. Finally, we set fire-prone pixels as those pixels with "high" or "very high" Wildfire Hazard Potential according to Scott et al. (2020) [140] (**see Figure 2-12**).

Biomass in the Fire-Prone Wildland-Urban Interface

Figure 2-13 shows a result of the high-fire, wildland-urban interface, TreeMap subset. The map depicts the amount of aboveground biomass (in metric tonnes) of fire-prone forests within the wildland-urban interface. The greatest concentration of fire-prone aboveground biomass in the wildland-urban interface is in California (48,962,000 tonnes), whereas Nebraska has the lowest (34 tonnes). Josephine

BOX 2-6

Forest Complexity and the Necessity of Local Forestry Knowledge

In the large spatial extent of this case study on dry western forests, the different forest types considered show tremendous variation. As such, the ways we manage these forests, even within the one objective of improving wildfire resilience, also have great variation. We modeled treatments using a technique—percentages of the maximum stand-density index (see main text)—that gave the flexibility needed to model treatments across the large land area of the case study. Our methods and results helped explore how managing forests for fire resilience could have beneficial carbon outcomes and approximated where such treatments could have large impacts. However, our process is not prescriptive as to what the best treatment for any given forest should be. Deciding which treatment any particular forest needs should rely upon the regional expertise of local forest scientists and managers.

County, Oregon is the county with the largest amount of wildland-urban interface fire-prone biomass (4,130,000 tonnes), followed by Nevada County, California (3,875,000 tonnes) and El Dorado County, California (3,798,000 tonnes).

Modeling CO_2 Emissions from Managed and Unmanaged Forests

For all forests identified in the fire-prone wildland-urban interface, we modeled effects on carbon storage from 6 possible management options: (1) no thinning or burning, (2) only pile burning, or (3–6) thinning to 1 of 4 possible target tree densities and then pile burning. We used a common forestry metric that reflects the number and size of trees (the stand-density index (SDI)) to determine thinning targets. The maximum stand-density index (SDImax) represents the maximum number and size of trees per unit area that have ever been observed, proportional to species. We used percentages of SDImax [124, 141] for different treatment intensities: 40%, 35%, 30%, and 25% of SDImax. These management options represent realistic versions of management actions that could be taken in any dry, fire-prone forest of the western United States. However, owing to uncertainties in our combined map, we have low confidence that any given prescription is “the correct” management option for a given pixel, given the aggregated uncertainty of combining multiple maps and the necessity of local knowledge in selecting optimal management (**Box 2-7**).

We first used the subset we had from TreeMap to query the USFS FIA database for multi-variable tree-level data [142]. We used the Forest Vegetation Simulator (FVS; [143]) and its Fire and Fuels Extension (FVS-FFE; [144]) to model the effects of wildfire on total forest carbon for each pixel with (management actions 2-6) and without (no thinning or burning) treatment. Our model accounts for the likely intensification of fire frequency and severity in the western United States by assuming a fire will occur, especially as we consider a subset pixels with a high or higher wildland-hazard potential and thus have a high likelihood of high-severity fire.

For all forested pixels within the wildland-urban interface, we modeled each of the six management options. The forest-treatment and fire-response model in the Forest Vegetation Simulator applied the following structure to each forested pixel: thinning treatment (or not) in 2023; pile burn (or not) in 2024; wildfire in 2025; followed by continuing the tree growth model until 2050. From each model run, we extracted total stand carbon in 2023 and 2050, total tree-biomass extracted from the treatment in 2023, fire emissions from the pile burn in 2024, and fire emissions from the wildfire in

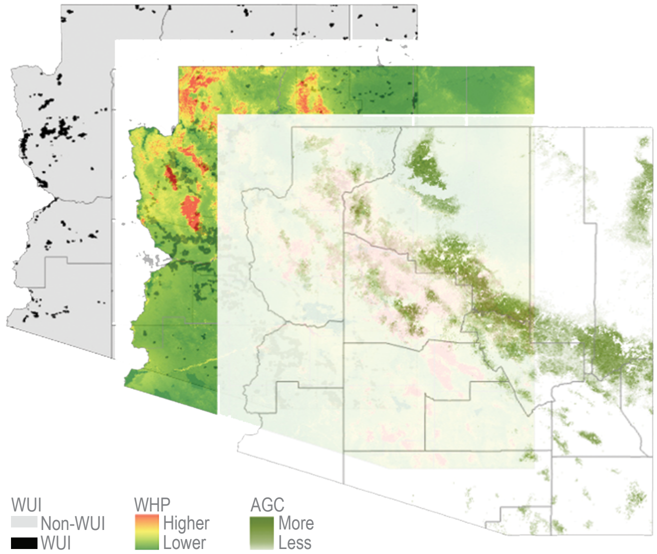


Figure 2-12. *A visual representation of the forest-pixel subset process, using Arizona as an example. We considered forest pixels for treatment if they met the following conditions: fall within US Forest Service (USFS) Regions 1–6; fall within the wildland-urban interface (WUI; interface or intermix); and have high or very high Wildfire Hazard Potential (WHP; an index that measures where fires may occur that are difficult to control). Here, the TreeMap layer—which indicates the most similar US Forest Service (USFS) Forest Inventory and Analysis (FIA) plot for any given pixel—is shown representing the relative aboveground carbon (AGC) of each pixel's plot.*

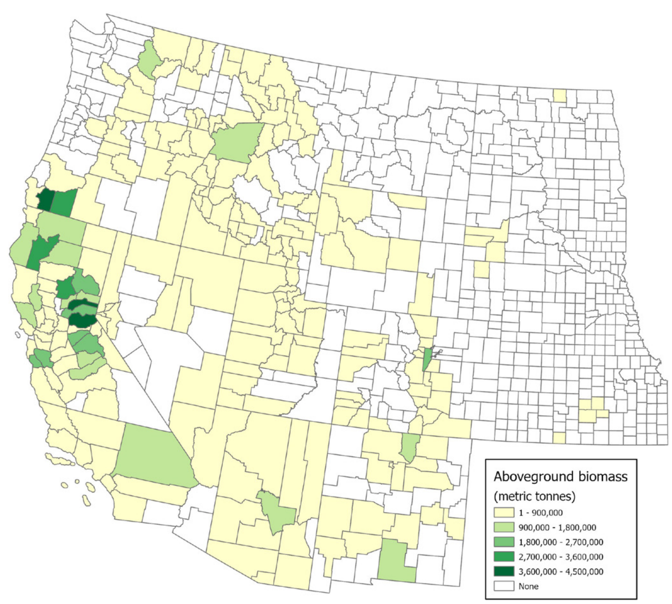


Figure 2-13. *Aboveground living biomass (tonnes) in the fire-prone wildland-urban interface by county. This map does not represent additional carbon from treatment; it is a snapshot of current biomass that is at high risk of fire near communities.*

BOX 2-7

Uncertainty and Humility in Carbon Accounting with Fire Prediction

This modeling approach—at this massive spatial extent—is novel. It draws on the best available science and models (most of which were created by researchers in the United States Forest Service). However, these models—like all models—are imperfect, and our analytical process is a composition of many models that each serve a distinct purpose, meaning their uncertainties are compounded. In particular, it is very challenging to precisely predict where a future fire will occur. As a result, there is not scientific consensus on how to incorporate fire likelihood into carbon accounting models. On the one hand, the likelihood of fire occurring in a particular forest in any given year is quite low. On the other hand, the likelihood that the same forest experiences fire in the relatively near future is quite high. With this in mind, our results are projections of potential forest carbon outcomes from fire-resilience treatments, serving to illustrate the carbon benefits of forest management but not estimates of the carbon outcomes that will ultimately be realized. In addition, we focus only on the wildland urban interface, and where fuel reduction logistically and economically feasible in wildland forests beyond that interface, potential carbon benefits could be much greater.

2025. We calculated the effect of each management action (2–6) as the with-treatment total stand carbon at year 2050 minus without-treatment (no thinning or burning) total stand carbon at year 2050.

We then selected whichever treatment—including no treatment or just pile-burn treatment—had the greatest increase in total stand carbon in 2050 compared to no treatment. We considered no treatment to be our baseline scenario because we were modeling the carbon benefit of catastrophic-fire avoidance through treatment and also because there is a limited wood-harvesting economy surrounding these forests [145]. We acknowledge that regional silviculturists and foresters would bring a nuance and expertise to actual on-the-ground treatments that we cannot capture with a model of our spatial extent (Box 2-6), but we hoped that selecting the "best" treatment out of the six would bring us closer to that nuance than a blanket prescription. Finally, we assumed a unilateral per-acre treatment cost based on numbers from Chang et al. [146] and decided on \$2471/ha (\$1000/acre) as it fell within the range of prices and agreed with a rule-of-thumb cost estimate. Thus, we calculated cost-per-tonne values as (\$2471/ha) / (tonnes of CO_2e per ha). This cost is likely an underestimate of true cost as it only includes the cost of the primary thinning operation; it does not include litigation expenses, nor does it include costs of revisiting the stand for maintenance thinning and burnings.

We Can Store More Carbon by Treating Forests for Fire Resilience

Our analysis shows that we could store an additional 16.21 million tonnes of CO_2e by 2050 by treating 0.48 million ha (1.19 million acres) of fire-prone forests in the wildland-urban interface in the conterminous western United States. The amount of additional carbon stored in any given forest varies significantly, from 0 to 1230 tonnes of CO_2e per ha. The per-pixel average amount of additional stored carbon is 33.8 tonnes CO_2e per ha (13.7 tonnes CO_2e per acre).

Because we calculate cost-per-tonne as treatment-cost-per-hectare / tonnes-per-hectare-from-treatment, the per-tonne cost of additional carbon also varies significantly, approaching infinity as additional stored carbon approaches zero (or infinity when the additional carbon value is zero). As a result, the average per-tonne cost for the full, theoretical additional storage amount (16.2 million tonnes of CO_2e) is very high: \$1876/tonne CO_2e. If we restrict the forest area, treating only areas with a reasonable cost (maximum of \$200/tonne), the average price declines to \$47/ tonne CO_2e, with a maximum additional storage of 16.0 million tonnes of CO_2e across 0.13 million ha (0.31 million acres). **Figure 2-14** describes additionally stored carbon depending on the maximum cost-per-tonne.

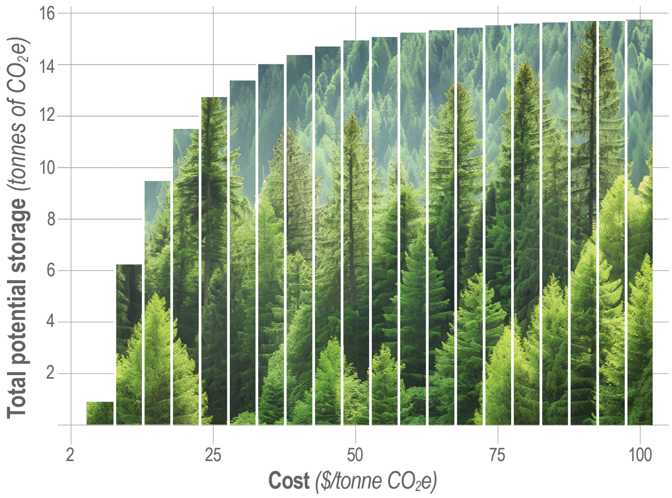


Figure 2-14. *Treating 0.13 million hectares (ha) (0.31 million acres) of fire-prone forests within the wildland-urban interface of the western United States could reduce total CO_2 loss to the atmosphere after wildfire. A sizeable portion of the region could be treated at less than $50 per tonne. This supply curve shows the potential additionally stored carbon from fire-resilience management based on a maximum cost-per-tonne of CO_2e, in $5/tonne increments. We only show to a maximum cost of $100/tonne, as all remaining cost increases resulted in nearly imperceptible total-storage increases.*

Most Additional Carbon Storage Comes from Avoiding Crown Fires

Treating forests to prevent crown fires provides the majority of additional storage: 12.1 million tonnes of CO_2e, which is 74.9% of the total potential additional storage. We identified 77,000 ha (190,000 acres)—16% of the total considered area—where applying a fire-resilience treatment stopped the occurrence of a crown fire. In other words, on these acres, without treatment a crown fire occurred, and with treatment a crown fire did not occur. These results demonstrate the importance of avoiding catastrophic crown fires through fire-resilience treatments. Furthermore, our results only project to 2050. Extending the time horizon of the analysis would likely increase the perceived climate benefits of avoiding high-severity crown fires, as avoiding these fires reduces the conversion of forests to non-forested ecosystems after catastrophic fire. Since these non-forested ecosystems have lower carbon storage capacity than forests, this avoided conversion provides longer-term increases that would only be observed with a longer time horizon of analysis.

Storing biomass from harvests would increase the amount of additional stored carbon. The treatments we modeled removed 4.5 million tonnes of CO_2e from the forest landscape through harvests. As noted above, there is currently little market opportunity to use much of this biomass in products that have a climate benefit, so the results we report here assume that all biomass from harvests is immediately emitted to the atmosphere. If we could store this biomass in long-lived wood products or biochar or use it for energy, we would store significantly more CO_2. In **Chapter 6 – BiCRS**, the authors estimated the costs and carbon benefits of constructing new biomass facilities to use this wood material; here, we provide a complementary estimate of the additional carbon gains to forest-carbon pools through biomass removal in fire-prone forests , this avoided conversion provides longer-term increases that would only be observed with a longer time horizon of analysis.

Storing biomass from harvests would increase the amount of additional stored carbon. The treatments we modeled removed 4.5 million tonnes of CO_2e from the forest landscape through harvests. As noted above, there is currently little market opportunity to use much of this biomass in products that have a climate benefit, so the results we report here assume that all biomass from harvests is immediately emitted to the atmosphere. If we could store this biomass in long-lived wood products or biochar or use it for energy, we would store significantly more CO_2. In **Chapter 6 – BiCRS**, the authors estimated the costs and carbon benefits of constructing new biomass facilities to use this wood material; here, we provide a complementary estimate of the additional carbon gains to forest-carbon pools through biomass removal in fire-prone forests.

No Single Treatment Alone Is Universally Effective

No single fire-resilience management treatment was effective across the entire forest landscape (**Figure 2-15**). Applying a single treatment to all forests led to effort and funding spent on some forests that saw no carbon benefit from that particular treatment and treating other forests in a suboptimal way. As a result, most treatments—when universally applied—had detrimental carbon outcomes where more CO_2 was emitted to the atmosphere in the treated scenario compared to if we had done no management across the entire forest landscape (Figure 099a). Even making the assumption that all harvested wood biomass would be stored in wood products, we found the highest mean difference in total stand carbon in 2050, for a single treatment universally applied, was 12.16 tonnes of carbon per ha (Figure 099b).

Instead of modeling one treatment universally across the landscape, we tried to mimic local expertise and decision making by choosing whichever treatment—including no treatment—had the most beneficial carbon outcome. The majority of forest pixels (64.2%) had no treatment as the best option; 18.0% had just a pile burn; 9.3% cut to 40% of SDImax; 4.0% cut to 35% SDImax; 2.6% cut to 30% SDImax;

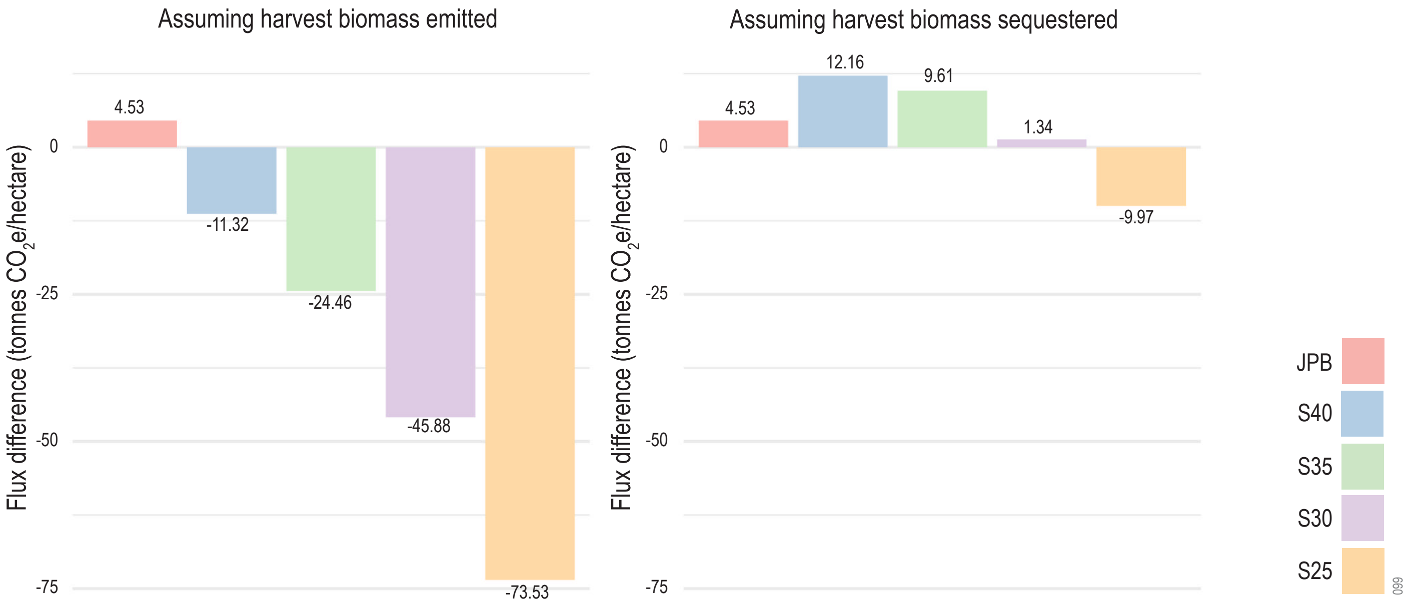


Figure 2-15. *Applying the same, universal fire-resilience management practices to 0.48 million hectares (ha) (1.10 million acres) of fire-prone forests in the wildland-urban interface of the western conterminous United States nearly always leads to more CO_2 emissions to the atmosphere relative to no treatment actions. We modeled treatments based upon levels of maximum stand-density index (SDImax)—a relative measure of how densely stocked a forest stand is, based upon species, number of trees, and size of trees. The five management treatments included the following: just pile burn (JPB); 40% SDImax (S40); 35% SDImax (S35); 30% SDImax (S30); 25% SDImax (S25). Negative values indicate increased emissions compared to the no-treatment scenario. Left panel assumes harvested biomass is immediately emitted, whereas right panel assumes the carbon in harvested biomass is not immediately emitted to the atmosphere and is stored long-term.*

and 2.1% cut to 25% SDImax. These results again highlight the importance of local forestry knowledge and expertise—beneficial climate outcomes will only result from effective, informed treatment decisions (Box 2-6).

3.3 Silvicultural Forest Management of Southern New England Forests

Overview

In this case study, we evaluated how implementing regenerative silvicultural practice in southern New England and southeast New York (**Figure 2-16**) could increase the forest CO_2-removal efficiency (**Section 2.2**) and the durability of forest-carbon stocks (**Section 2.3**).

Forests in this region are second-growth forests that are recovering from wide-spread clearing during the 18th and 19th centuries (**Section 1.1, Box 2-2**). Approximately 80% of the total forestland in the study region are oak-mixed hardwood and northern hardwood forests, which are the two most widely distributed forest types in the northeastern region of the United States [75]. These hardwood forests provide a multitude of services, including serving as critical habitat for wildlife [147], protecting and cleaning municipal water supplies [148], providing tourism and recreation opportunities, and providing home heating and supplemental income for small family-forest landowners [149, 150].

There is limited forest-management planning or commercial-harvesting activities in this region. Currently, nearly 70% of the forestlands in the region are privately owned by family-forest landowners, with very little industrial corporate ownership [120, 151] (Figure 2-3). Over 70% of family-forest owners value the beauty, scenery, and privacy of their forestlands, while fewer than 20% value their forests for timber production. Fewer than 10% of these family-forest landowners have forest-management plans for their property, and ~20% have harvested trees for personal income [152].

When forests in the region are harvested for profit, the dominant harvest approach is “exploitative harvests” that prioritize short-term revenues over long-term goals, such as maintaining species, age, and structural diversity or fostering high-value species. Exploitation-focused harvests remove the largest and most valuable hardwood trees [153, 154] and cause degradation of New England’s forests [155]. These degraded forests are likely less resilient to future climate-related risks (**Section 2**) and have lower future growth and productivity; they are thus less efficient at capturing CO_2 and more at risk to losing carbon stocks to natural disturbances [155].

Exploitation-focused practices in the region depart from best-practice silvicultural prescriptions [154-156]. These best-practice treatments, which we call "regeneration-focused" treatments, prioritize the long-term health and sustainability of forests by promoting regeneration of a diverse and climate-resilient suite of tree species. These regeneration-focused harvest practices may also be able to restore the health of degraded forests. In doing so, regenerative harvests may also meet the goals of state public-forest-management agencies who seek to promote a diversity of ecosystem services provided by forests, including CO_2 removal, water-quality protection, biodiversity conservation, and recreational value [135, 157, 158].

In this case study, we projected the consequences of these three regionally (southern New England and New York) most common forest-management decisions—no harvesting, exploitation-focused harvesting, and regeneration-focused harvesting—on forest carbon stocks and future CO_2-removal potential. These forest-management options are central to current debates between public and private forest landowners, policy makers, and forest advocates on the "best" strategies for protecting and managing the region's forests. These stakeholders care not only about the potential of the region's forests for carbon removal and storage, but also about ensuring that their forestlands continue to support the range of services important to the diversity of stakeholders in the region [152].

Approach

Using 2202 forest inventory plots from federal and state forest management agencies (**Figure 2-16**), we simulated changes in forest-carbon stocks in response to no harvesting, exploitation-focuses harvesting, and regeneration-focused harvesting (Box 2-6). Exploitation-focused harvesting is a general term for a suite of tree-harvest practices that prioritize short-term revenues of high-value timber [153, 154]. For our study region, a common exploitative-harvest practice is diameter-limited harvests that periodically remove large trees above a diameter threshold related to regional timber values. Regeneration-focused harvesting is also a general term and is, for our region, a shelterwood harvest system that showed successes in regenerating and diversifying northeastern US oak forests [159, 160].

For our case study, we used the terms "passive management" to describe forest management with no harvests, "exploitation-focused management," to describe forests harvested by diameter-limit cuts, and "regeneration-focused management" to describe forests harvested by shelterwood cut. We emphasize that we made our selection of these three harvest strategies to allow us to simulate potential forest-carbon outcomes across a region; actual implementation across the landscape would require site-specific prescriptive management that considers the current tree-species composition and structure, past management, and future risks by foresters with local knowledge and expertise (Box 2-6).

We also included common natural disturbances in our model simulations to explore how management decisions change

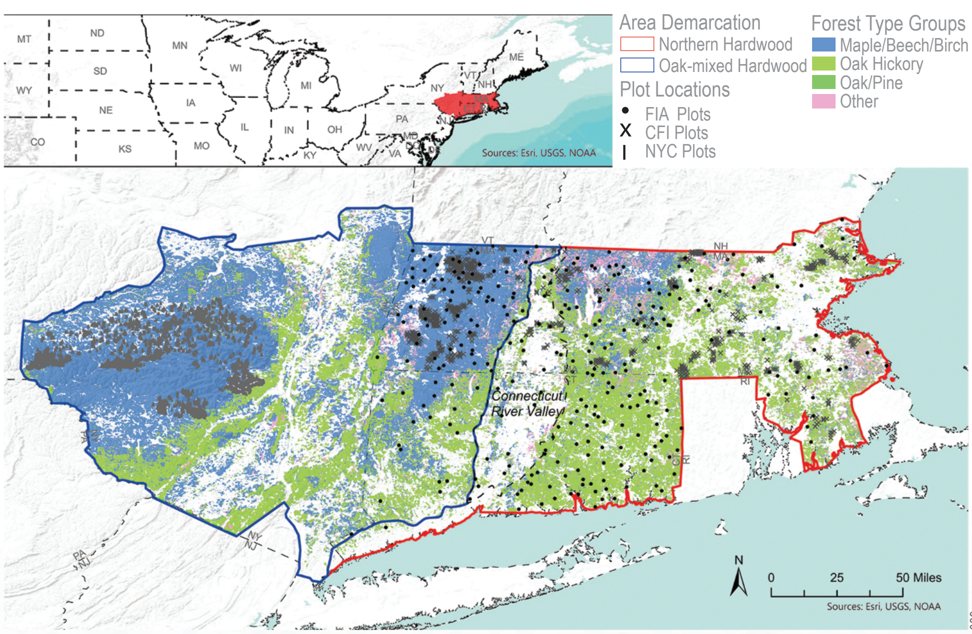


Figure 2-16. *Location of the study region, area demarcation, distribution of forest types, and locations of forest inventory plots used in this case study. The forest-type groups are based on the US Forest Service (USFS) national algorithm [84], in which Maple/Beech/Birch represents Northern Hardwood and Oak/Hickory and Oak/Pine represent Oak-mixed Hardwood. Forest Inventory and Analysis (FIA) data (n=183) were provided from USFS [85]; Continuous Forest Inventory (CFI) data (n=681) were provided from the Massachusetts Department of Conservation & Recreation [86]; and New York City watershed data (n=1228) were provided from the New York Department of Environmental Protection [87].*

forest CO_2-removal efficiency or durability of forest carbon stocks. Increasing droughts windstorms, and more frequent pest and pathogen outbreaks all threaten the region's forests (**Section 2**). These climate-related stressors reduce the forest's carbon-removal efficiency and the future capacity for carbon storage, and they are already common. We modeled the following two disturbance regimes: extreme weather (drought and windstorm) and extreme weather coupled with pest and disease outbreaks (Emerald Ash Borer, *Agrilus planipennis*; Spongy Moth, *Lymantria dispar*; and beech leaf disease, *Litylenchus crenatae mccannii*; Appendix 2).

We simulated the effects of forest management and natural disturbance using the Northeastern variant of the USFS Forest Vegetation Simulator [161] (**Figure 2-17**). This tool is a forest-growth and-yield model used for projecting forest-stand development by foresters [162] and is a standard tool in carbon-offset protocols [163]. We simulated the management approaches by setting the rotation length, target tree diameter, and residual forest basal area of the cutting. We manually modified tree mortality rates to emulate natural disturbance. We harvested forests at Year 0 and simulated 100 years of growth.

To estimate the total carbon benefits of each forest-management approach, we estimated carbon accumulation in different forest-carbon pools and in wood products, which are considered part of the total forest-carbon budget in the US GHG Accounting framework (**Section 1**) [25]. We accounted for "avoided emissions" from substitution effects of the woody bioenergy using displacement factors from a global literature review [105]. Below, we present the total climate benefit as the total forest carbon stored in forest-carbon pools, wood products, and net atmospheric gains from avoided emissions. We note that, in most accounting frameworks, the "avoided emissions" benefits of wood-product substitution are not included in the forest-carbon budget [25]. We provide regional averages across the forest types (Figure 089; See **Appendix 2**).

Effects of Management and Disturbance on Forest-Carbon Storage

Overall, regeneration-focused forest management can promote forests that are more resilient to natural disturbances relative to exploitation-focused management or passive management. The carbon benefits of these practices, however, are only achieved over longer time horizons or if you include the climate benefits from avoided emissions with wood-product substitutions. The relative benefits of forest management for protecting forest carbon and promoting CO_2 removal depend on the presence of natural disturbances, the

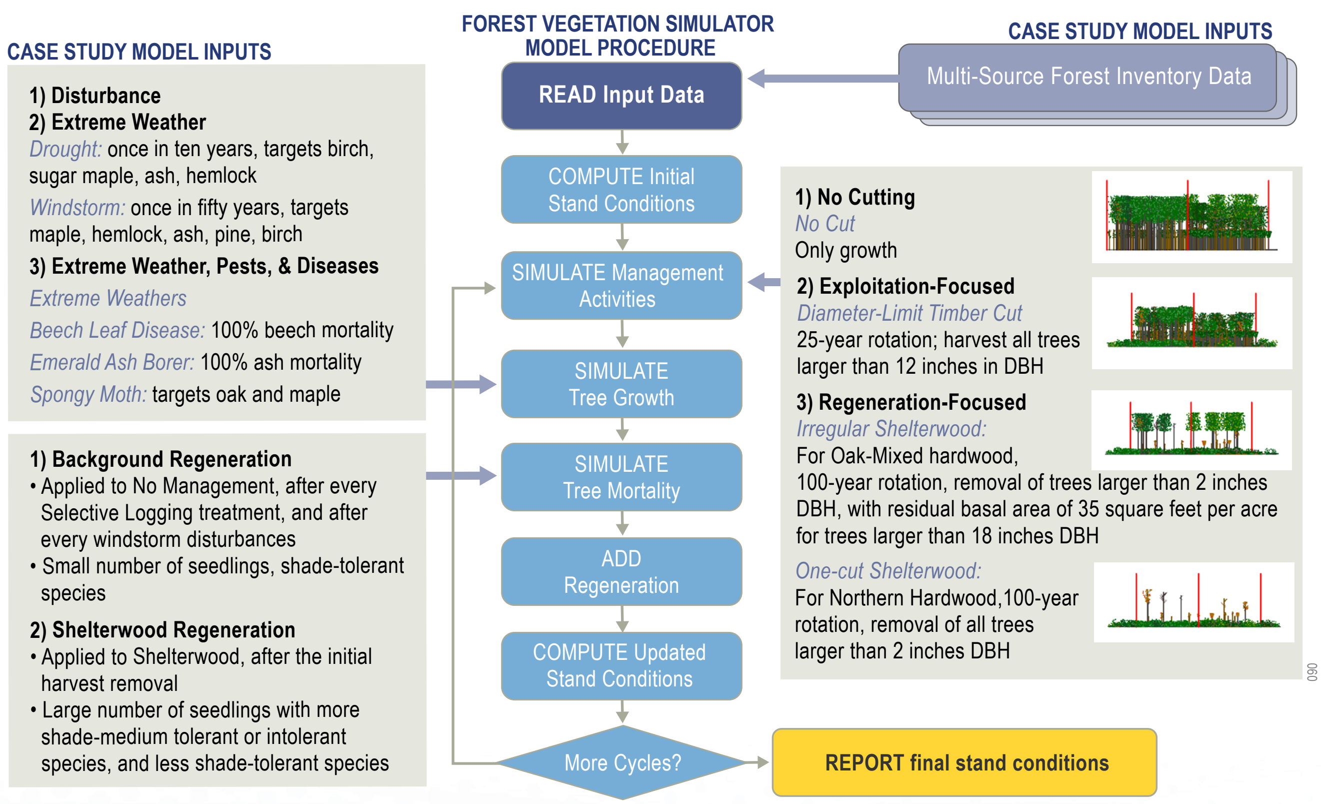


Figure 2-17. *Model inputs and model proceedure used within the Forest Vegetation Simulator [161]. Pictures of forest stands illustrate management effects produced by the Forest Vegetation Simulator. DBH = diameter at breast height.*

time horizon of interest, and whether the accounting scheme includes the climate benefits of avoided emissions from wood-product substitution.

When forests are undisturbed, passive management without harvest accrues ~30% more carbon in the forest than either harvest scenario. However, both harvesting strategies led to higher climate benefits when accounting for carbon in wood products and avoided emissions (**Figure 2-18**). Passive management leads to steady carbon accrual as trees grow, with carbon accrual rates slowing across the 100-year simulation period (Figure 091a). Forest harvest in Year 0 reduces total forest-carbon storage, whether the harvest is exploitation-focused (Figure 091b) or regeneration-focused (Figure 091c). Approximately 45 years after harvest, the total climate benefit of harvesting practices become equivalent to the total carbon storage within forest-carbon pools in the passively managed forests.

Extreme weather and pests and diseases within passively managed forests cause 40% decline in forest-carbon stocks after 25 years. The effects of extreme weather events and pest and disease outbreaks led to an 80% decline in living-tree biomass (**Figure 2-19**). Our natural disturbance simulations represent a realistic, common, but severe natural disturbance on one single forest stand. Dead trees remained in forest carbon pools as standing dead biomass and as downed woody material, eventually decaying and emitting CO_2.

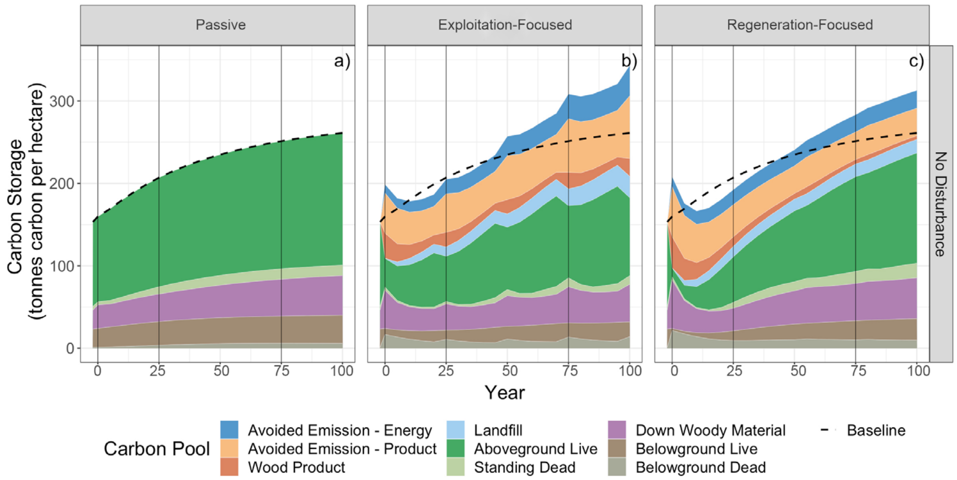


Figure 2-18. *Projection of carbon storage in forest-carbon pools, wood products, and avoided emissions over 100 years with no forest disturbance for three forest-management practices in southern New England and New York forests. (a) Passive management simulated forest growth with no harvests, (b) exploitation-focused management (implemented multiple tree harvests to maximize short-term profits), and (c) regeneration-focused management (implemented a single harvest to promote regeneration of diverse and climate-resilient suite of tree species). Dashed line in (b) and (c) represents the total carbon storage under passive management, and solid vertical lines denote carbon stocks in 25 and 75 years.*

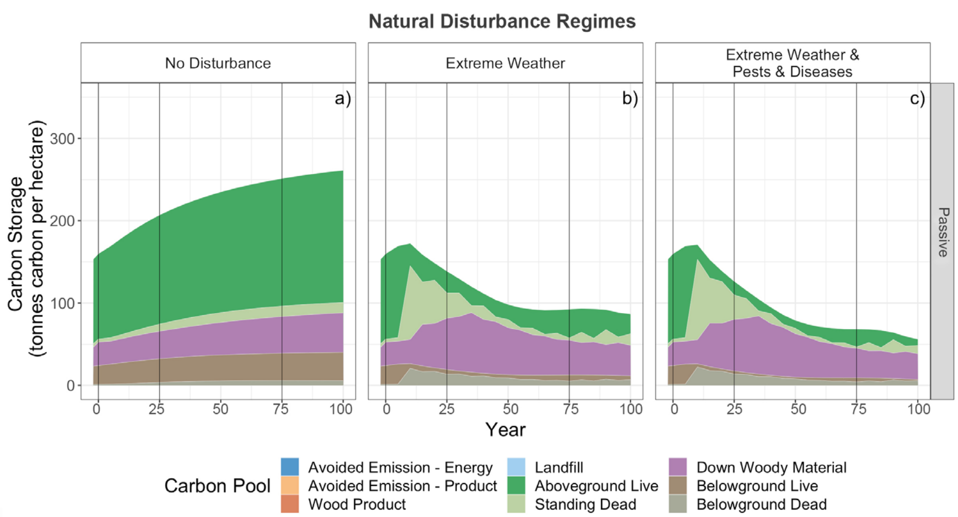


Figure 2-19. *Effect of natural disturbances on forest-carbon storage in a passively managed forest with no harvests. We simulated forest-carbon stocks under (a) no disturbance, (b) extreme weather (drought and windstorms), and (c) extreme weather plus pests and diseases.*

After 100 years under extreme weather and pests and diseases, regeneration-focused management stored ~50% more carbon in the forest-carbon pools and wood products than passive management or exploitation-focused management. The total climate benefits of regeneration-focused management were more than double the carbon storage in forests under passive management and ~10% higher than the total climate benefits of exploitation-focused management (**Figure 2-20**). Forests treated with regeneration-focused management experienced lower carbon losses with natural disturbances and faster accrual of the lost carbon storage relative to passive management. However, it took time for the carbon benefits of regeneration-focused management to accrue. It took ~30 years for the young trees in the forests managed with regeneration-focused harvests to regain forest-carbon stocks equivalent to the forest-carbon stocks of passively managed forests. After 75 years, forests managed with a regeneration-focus had nearly two times larger forest carbon stocks than forests managed passively (Figure 093 e,f). If accounting for the climate benefits of wood-product substitution, the total CO_2-removal potentials of regeneration-focused management are 23%–29% higher than the climate benefits provided by passively-managed forests under natural disturbances after 25 years (Figure 093 b,c,e,f).

One key issue our results raise is that managers must evaluate the risk of a severe natural disturbance in their forest. Congruent with other studies in the region [162, 164, 165], we found that, under model simulations with no additional tree mortality, passive management of forests provides the highest CO_2-removal potential within 25 years, relative to either harvesting scenario. However, given the historical frequency of disturbances and the projected increases in pests, diseases, and climate stressors for the region (Section 1) [166], the likelihood of "no disturbances" may be quite low. Between 2000 and 2016, about 10% of the region's forestlands experienced at least one disturbance event that damaged tree canopies [167]. The northeastern United States has already experienced a multi-year outbreak of spongy moth (*Lymantria dispar*) that led to widespread forest-canopy defoliation across 438,600 ha (1.08 million acres) [168]. The emerging beech-leaf disease complex is rapidly spreading in New York and southern New England and is causing beech-tree (*Fagus grandifolia*) mortality within 2–6 years of detecting infection [169, 170]. Additionally, the northeast is a hotspot for outbreaks of non-native pests (compared with all other regions) [71], suggesting this region may have the highest probability of novel introductions of new forest pests or pathogens.

Uncertainty and Limitations

First, we applied three representative forest-management practices universally across all forest-inventory plots. There is no one-size-fits-all management approach to forest management; all forests likely require unique prescriptions based on the structure of the forest stand, objectives of management, and anticipated disturbances, which will be best assessed within the forest by local foresters (Box 2-6). Second, we did not consider the stochasticity of natural disturbances in our analysis, which could change projected outcomes, nor did we consider other disturbances, such as

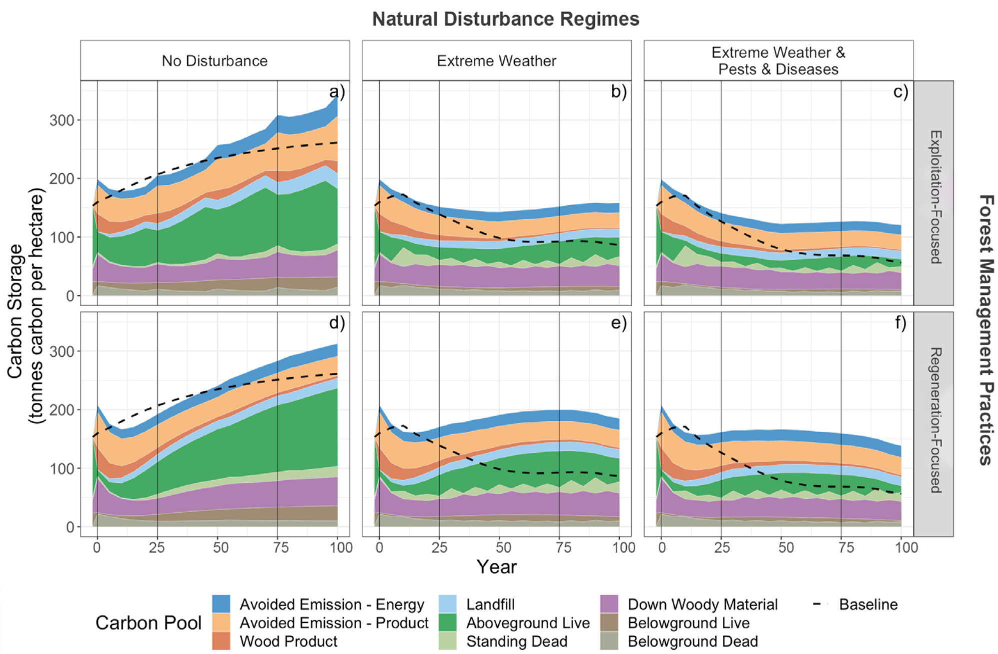


Figure 2-30 *The effect of exploitation-focused (a–c) and regeneration-focused (d–f) forest management under simulated no disturbance (a, d), extreme weather (drought and windstorm; b, e), and extreme weather plus pest and disease outbreaks (c, f). The dashed lines represent total carbon storage in a passively managed forest under similar disturbance conditions (Figure 092). Regeneration-focused management led to lower carbon losses and faster recovery of carbon storage following disturbances after 100 years. By 25 years after harvest, the total climate benefits of regeneration-focused management were ~30% higher than the carbon storage in passively managed forests.*

wildfire or herbivore over-browsing. Third, our modeling tool does not project the impact of future climate change on tree growth. Changing climates may lead to vegetation shifts [171] or altered mortality and growth rates

Estimated Costs and Supply of the CO_2-Removal Potentials

Our model simulations present the "average" carbon gain or loss across all forest plots. To estimate the potential CO_2-removal benefits of management for the region, we made two assumptions. First, we assumed that passive forest management with no harvest was the common baseline practice in the region, based upon prior landowner surveys [152]. Second, we assumed the proportion of regional forest that was harvested each year. Individual silvicultural prescriptions are generally assigned to forest stands, rather than being assigned across an entire forested landscape. Instead, foresters may harvest a percentage of forestland each year to rotate management across the landscape and through time. Thus, we implemented annual harvests on 2% of forestlands [135] and using USFS EVALIDator data to estimate total forestland area [151]. To estimate the total CO_2-removal potential of these practices across the landscape, we calculated regional totals per year by multiplying forest areas at different years after harvest—following the 2% annual harvest rate—with the average per-hectare CO_2-removal potentials from **Table 2-2**.

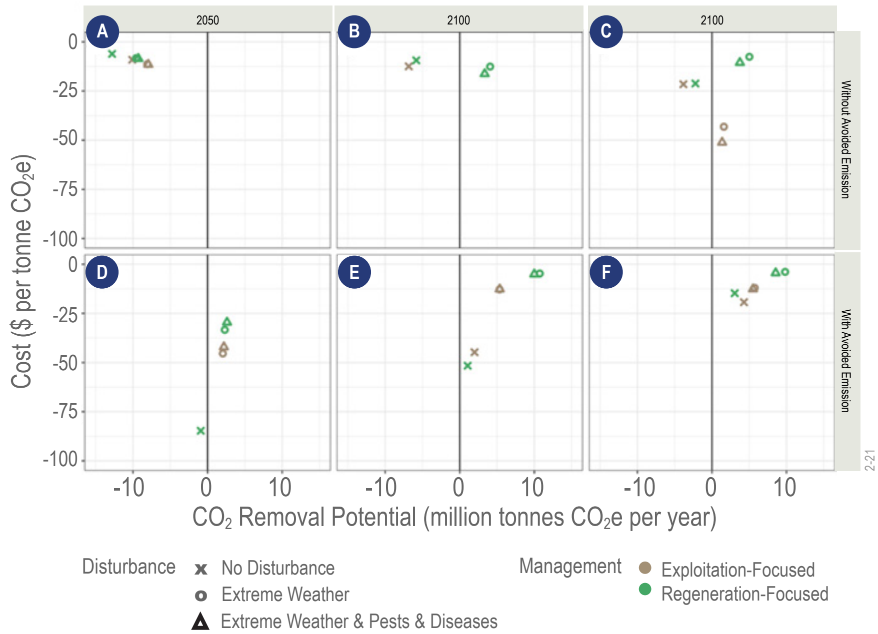
To estimate the costs of implementing harvest practices, we used regional stumpage prices [172] to represent the balance of harvest costs and timber-sale revenues from the forest landowner's perspective. Because most forests in the region are owned by small family-forest owners [120, 151], landowners will outsource timber harvests to logging companies. These companies pay stumpage prices based on the size and species of trees they remove from the forest. We note that use of single time-point stumpage prices introduces uncertainty into these calculations, as stumpage prices can fluctuate widely as timber-market demand changes. Further, these prices only reflect a balance of timber values and harvest operational costs, which do not include any other site-specific treatments, such as stand-improvement practices. To estimate regional costs, we upscaled the stumpage prices per volume of timber of different tree species using the average per-hectare harvest volumes from the model outputs (**Appendix 2**).

Regeneration-focused forest management in southern New England and New York could provide 2.61 million tonnes of CO_2e per year by 2050, assuming the occurrence of common natural disturbances and including the climate benefits of wood-produce substitution. Forest-cutting practices provide net economic benefits, equivalent to over \$4/tonne CO_2e (**Figure 2-21**). When only accounting for carbon stored in forestlands and wood products, both harvest practices led to net carbon losses by 2050. Regeneration- and exploitation-

Table 2-2. *CO_2-removal potentials (tonnes of CO_2e per ha) of two harvest approaches—exploitation-focused and regeneration-focused—relative to a passive-management approach with no harvests. The CO_2-removal potential changes by disturbance regime (no disturbance (none), extreme weather (EW), or extreme weather plus pests and disease (EWPD)) and by time horizon after harvest (25, 75, and 100 years). The CO_2-removal potential is color-coded where red colors indicate forest-carbon losses and blue colors indicate forest-carbon gains with harvesting relative to no harvest. Values per forest type are presented as in Appendix 2, Table B4*

Per hectare CO_2-removal potential without avoided emissions				Per hectare CO_2-removal potential with avoided emissions			
Year 25	none	EW	EWPD	Year 25	none	EW	EWPD
Exploitation	-243	-129	-123	Exploitation	-7	48	53
Regeneration	-263	-93	-80	Regeneration	-53	117	129
Year 75	none	EW	EWPD	Year 75	none	EEW	EWPD
Exploitation	-139	61	55	Exploitation	210	219	213
Regeneration	-82	206	147	Regeneration	117	393	334
Year 100	none	EW	EWPD	Year 100	none	EW	EWPD
Exploitation	-114	107	81	Exploitation	300	263	237
Regeneration	-13	178	118	Regeneration	189	361	301

Figure 2-21. *Distribution of the cost-supply of CO_2-removal potentials of exploitation- and regeneration-focused management relative to passive management when accounting for carbon stocks in forests and wood products (a–c) and with avoided emissions from wood-product substitution (d–f). Assuming harvest rates of 2% of forestland per year begin in 2025, we projected cost-supply curves by 2050 (a, d), 2100 (b, e), and 2125 (c, f). Negative costs represent net profits of timber harvest for private landowners. Negative CO_2-removal potential represents net carbon losses from forest harvesting relative to no harvesting. Costs are disproportionally high when the CO_2-removal potential is near zero, and we do not include two points that had high costs (d, exploitation-focused management, 0.89 million tonnes of CO_2e per year at \$-764 per tonne and c, regeneration-focused management, -0.3 million tonnes CO_2e per year at \$-505 per tonne).*



focused harvest practices only provided net CO_2 removal after 2085 and 2100, respectively. When accounting for avoided emissions, exploitation- and regeneration-focused managements lead to net CO_2 removal equivalent to 0.4–2.6 million tonnes of CO_2e per year by 2050. However, we emphasize the ecological benefits to forest health of regeneration-focused management over exploitation-focused management, which suggests it should be the favored practice.

4. Forest Management from an Energy Equity and Environmental Justice (EEEJ) Perspective

In this section, we assess the potential co-benefits and negative impacts that might arise from the forest-management opportunities discussed in this chapter and make recommendations for maximizing co-benefits and minimizing potential negative impacts (**Table 2-3–2-5**).

One key benefit of forestry-based CO_2-removal methods in the southeastern and northeastern United States is preservation of forestlands. In the western United States, forestry-based CO_2-removal methods provide direct health benefits by preventing premature deaths due to wildfire smoke inhalation and economic benefits by reducing property damage incurred from wildfires [173-175]. In the southeastern United States, expanding loblolly pine plantations has significant workforce and economic potential. This industry is currently responsible for ~110,000 jobs and generates ~\$30 billion for this area's economy, which could grow if the industry is expanded [176].

The overarching potential negative impact for all three case studies in Section 3 is the potential to increase economic division of woodland-ownership disparities in the United States. Approximately 95% of US forest landowners are white [177], and white forest owners are more likely than minority forest owners to participate in forest-related economic-assistance programs [177]. Without equity enhancements that prioritize outreach and involvement of minority forest owners, forest CO_2-removal investments could disproportionately benefit white forest landowners over minority forest landowners. By increasing forestry CO_2-removal outreach to minority forest owners, including over 300 tribal governments who have sovereignty over more than two million acres of land [29], there is potential to reverse inequities in forest-management assistance. We also note that our analysis excludes the potential that urban forests have in mitigating climate impacts in cities, while also providing other important ecological and public health benefits (**Box 2-8**). Because US cities are, on average, more diverse than rural forested regions, urban forestry may provide a key opportunity for equity enhancements in forestry CO_2 removal.

To efficiently synthesize socioeconomic and environmental data relevant to DOE's energy equity and environmental justice (EEEJ) goals, we constructed an average EEEJ Index value for each forest-based CO_2 removal case study in this report (**Chapter 9**). In these indices, values closer to 1 represent high opportunities for co-benefits, and values closer to 0 represent lower likelihood for co-benefits and potentially greater challenges pertinent to EEEJ considerations. The impact of each variable, positively or negatively, on the overall EEEJ Index value for each county

Table 2-3. *Potential co-benefits and negative impacts of forest-based CO_2-removal methods, alongside recommendation for maximizing benefits and minimizing risks.*

NORTHEAST FOREST MANAGEMENT: STRATEGIC LOGGING FOR STAND AGE DIVERSITY	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Biodiversity and hunting opportunities Prioritize large, young stands with low species diversity to see the largest return for given effort [173].	Noise pollution Use electric machinery to reduce noise pollution [179].
Direct jobs Local hiring commitments and compensation—that bear in mind the inherently difficult and seasonal nature of logging work—could be negotiated in labor workforce and community benefit agreements in advance of a project [180].	Traffic impacts Prioritize management efforts in regions not identified as being unduly impacted by traffic [181].
Indirect jobs An open-source economic model to forecast potential indirect job creation could be incorporated in pre-project community benefit discussions [182].	Decreased privacy Optimize for privacy maintenance in harvesting timeline/design with input from landowner to protect places they frequent [182].
Resilience to disturbances Design custom forest-management protocols optimized to reduce disturbance risk [3]	Overpromised/unrealized performance Leave multiple species of old-growth individuals in cleared acreage [3]. Perform baseline assessment such that results can be compared against a rigorous counterfactual [183].
County and state tax revenue Project developers and local officials could make efforts to receive direct and sustained public participation in determining how tax revenues from forestry are committed to local causes [184].	Aesthetic Maintain several large trees that have interesting branch patterns and attractive fall foliage in areas that landowners say they frequent, cut stumps low to the ground, and remove all debris upon departure [182].
Reduced tree mortality Thin overly dense forests, and support species diversity to reduce tree mortality risk [185].	Economic division Historic access to land ownership is not equally distributed and regional maps of private forest/woodland ownership demographics (**Chapter 9**) could be consulted pre-investment to assess equitable distribution potential [177].
	Industrial forestry presence Maintain perimeter stand of trees to minimize visible presence, and optimize to operate as far from residences as reasonable [182].
Renewable-energy generation Prioritize rural communities in need of decarbonized power, and quantify conservative regional harvest yields that can consistently provide demand-matched power.	Competition with indigenous forestry practices Within tribal-land boundaries, indigenous forest-management practices should be discussed with stakeholders to design any management changes, including comparing the carbon-sequestration potential from indigenous forest management versus proposed management changes [187]. Avoid development on land with uncertain land tenure to circumvent disenfranchisement of local communities [183].

Table 2-4. *Potential co-benefits and negative impacts of forest-based CO_2-removal methods, alongside recommendation for maximizing benefits and minimizing risks.*

SOUTHEAST FOREST MANAGEMENT: REFORESTATION ON MARGINAL LANDS WITH LOBLOLLY PINE	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Community wealth Prioritize marginal lands that currently, or are forecasted to, bring little to no income for landowners [188].	Uncertain air quality impacts Conduct a regional air modeling analysis to optimize planting locations and transport routes that minimize PM2.5 production in counties currently experiencing negative public health impacts from diesel-derived PM2.5 [189]
County and state tax revenue Prior to project permitting, a citizens advisory panel should negotiate what percentage of revenue generation would be committed to causes based on public feedback [188].	Noise pollution Use electric machinery to reduce noise pollution [179].
Biodiversity and hunting Prioritize vacant, marginal lands that have been historically forested [188].	Traffic impacts Prioritize developments in regions without pre-existing traffic burdens [181].
Reduced tree mortality Thin overly dense forests, and support species diversity to reduce tree mortality risk [185].	Industrial forestry presence Maintain perimeter stand of trees to minimize visible presence, and optimize to operate as far from residences as reasonable [182].
	Competition with indigenous forestry practices Within tribal-land boundaries, indigenous forest-management practices should be discussed with stakeholders to design any management changes, including comparing the carbon-sequestration potential from indigenous forest management versus proposed management changes [187]. Avoid development on land with uncertain land tenure to circumvent disenfranchisement of local communities [183].
Direct Jobs Local hiring commitments and compensation that bears in mind the inherently difficult and seasonal nature of reforestation work should be negotiated in labor workforce and community-benefit agreements in advance of a project [180].	Timber price Economic modeling should be conducted to estimate scale-up capacity while maintaining economic viability
Indirect Jobs An open-source economic model to forecast potential indirect job creation should be incorporated in pre-project community-benefit discussions [190].	Ecosystem health Minimize soil erosion by planning and building road access that has minimal slope angles while facilitating drainage; regrade roads after logging activities [182].
Erosion control Plantations should be preferentially located in areas currently experiencing high soil-erosion rates due to low vegetation cover [188].	Economic division Historic access to land ownership is not equally distributed and regional maps of private forest/woodland ownership demographics (Chapter 9) could be consulted pre-investment to assess equitable distribution potential [177].
	Land competition A diversity of stakeholders should be involved in early discussions regarding land needed for critical community needs (e.g., housing, energy production, commerce, industry) to ensure that land converted to plantations does not infringe on community wellbeing [191].
	Overpromised/unrealized performance Perform baseline assessment such that results can be compared against a rigorous counterfactual [183].
	Water quality Watersheds with pre-existing eutrophication issues could be avoided due to additionality of fertilizer application in pine industry [192] and/or streamside management zones could be implemented to reduce eutrophication risk [193].

Table 2-5. *Potential co-benefits and negative impacts of forest-based CO_2-removal methods, alongside recommendation for maximizing benefits and minimizing risks.*

WESTERN FOREST MANAGEMENT: FOREST THINNING FOR WILDFIRE REDUCTION	
Potential **Co-benefits** to Communities & Options for Maximizing Potential Co-benefits	Potential **Negative** Impacts to Communities & Options for Minimizing Potential Negative Impacts
Recognition of indigenous forest-management practices Studies should be conducted that quantify net changes in carbon fluxes and stock changes in stands that become managed by individual tribes [187].	Smoke pollution from prescribed burning Divert wood residues to BiCRS for gasification or chip on site to avoid negative health impacts to surrounding communities from acute smoke exposure from prescribed burns (e.g., [194]).
Infrastructure protection Prioritize forest thinning at the wildland-urban interface [195].	Competition with indigenous forestry practices Within tribal-land boundaries, indigenous forest-management practices should be discussed with stakeholders to design any management changes, including comparing the carbon-sequestration potential from indigenous forest management versus proposed management changes [187]. Avoid development on land with uncertain land tenure to circumvent disenfranchisement of local communities [183].
Reduced forest mortality Thin overly dense forests, and support species diversity to reduce tree-mortality risk [185]. Prioritize stands that are currently dying of drought and/or conditions ideal for infestations.	Increased short-term runoff and soil erosion Pre-emptively assess erodibility using high-resolution models. Prioritize flatter stands with limited susceptibility to erosion for thinning first [196]. Sow fast-growing native groundcover seeds whenever feasible to reduce runoff [197].
Direct jobs Local hiring commitments and compensation—that bear in mind the inherently difficult and seasonal nature of forest thinning work—should be negotiated in labor workforce and community-benefit agreements in advance of a project [180].	Soil health Use designated or existing harvesting traffic lanes and leave some thinning residue in high-traffic areas to reduce soil compaction [198].
Indirect jobs An open-source economic model to forecast potential indirect job creation should be incorporated in pre-project community benefit discussions [190].	Noise pollution Use electric machinery to reduce noise pollution [179].
Soil health Prioritize thinning to regions exceptionally likely to experience wildfires—where whole stand removal may be under consideration—to prevent soil compaction and soil-health degradation [198].	Traffic impacts Prioritize developments in regions without preexisting traffic burdens [181].
Reduced smoke pollution Prioritize thinning to areas particularly prone to wildfire and situated in counties with especially vulnerable populations [174].	Industrial forestry presence Maintain perimeter stand of trees to minimize visible presence, and optimize to operate as far from residences as reasonable [182].
Renewable-energy generation Prioritize rural communities in need of decarbonized power, and quantify conservative regional harvest yields that can consistently provide demand-matched power [186].	Overpromised/unrealized performance Perform baseline assessment such that results can be compared against a rigorous counterfactual [183].

is presented in **Figures 2-22, 2-23,** and **2-24**. Following the construction of the EEEJ index, we conducted a comparison to the Center for Disease Control's (CDC's) Social Vulnerability Index (SVI) and each case study's CO_2 removal opportunity (potential tonnes of CO_2 removed by 2050) to facilitate a comprehensive evaluation of regional disparities and potential areas for targeted interventions (**Figures 2-25, 2-26,** and **2-27**). Evaluating SVI alongside this report's EEEJ Index may be useful for policymakers and project developers in determining priorities associated with forest-management opportunities, such as protecting a region's most vulnerable communities from wildfire, or in ensuring careful consideration around developing industrial presences (e.g., lumber mills) in a county less equipped to respond to potential emergencies. Further examination of the socioeconomic and environmental contexts considered for each county identified in the chapter can be found in **Chapter 9 – EEEJ**.

BOX 2-8

Urban Forests:
Environmental Justice & Carbon Removals

In the United States, there are about 730,000 hectares (1,803,869 acres) of natural area forests embedded in urban landscapes. In contrast to other urban tree canopy types, such as street trees, these natural area forests refer to densities and diversities of trees, with complex understories, that are more like rural forests. With four out of five Americans living in a city, these urban natural area forests provide a nature experience to a large proportion of the United States' population, with demonstrated benefits for health and wellbeing, including for urban communities most affected by environmental injustices. These natural area forests also appear to be where most trees and consequently carbon is found within the urban tree canopy. For example, despite only accounting for one quarter of the tree canopy in New York City, 69% of trees in the city were estimated to be in natural area forests. Of these forests, native-dominated vegetation types had higher carbon stocks and accrual rates where, for example, oak-hickory forests had average carbon stocks of 1,005 tonnes CO_2e ha^{-1}, 27% greater than degraded, invasive-dominated natural area forests. Ongoing assessments for other cities, such as Seattle, Baltimore, Indianapolis, and Chicago, find similar carbon stock values and that vegetation carbon is overwhelmingly stored by native tree species.

Unlike most forestlands that are under National, State, or private ownership, urban natural area forests are typically under the management of municipal agencies, making for a wide variety in the attention paid to, and the management and protection of, these forestlands. However the collective benefits of native-dominated, natural area forests for the health of the urban populace and their high carbon stocks per unit area, highlights the need for collaborative efforts both locally and nationally to protect this natural resource from being degraded (by, for example, invasive species) and converted to other land-uses. A national coalition to enumerate natural area forests and advance best practices for their stewardship is emerging through the Forests in Cities Program [164].

The support of such efforts through coordinated national policy can raise awareness and support for sustaining and growing native-dominated, natural area forests in urban areas, and for a full accounting of how they may contribute to achieving atmospheric CO_2 drawdown.

NORTHEASTERN FOREST STAND DIVERSIFICATION

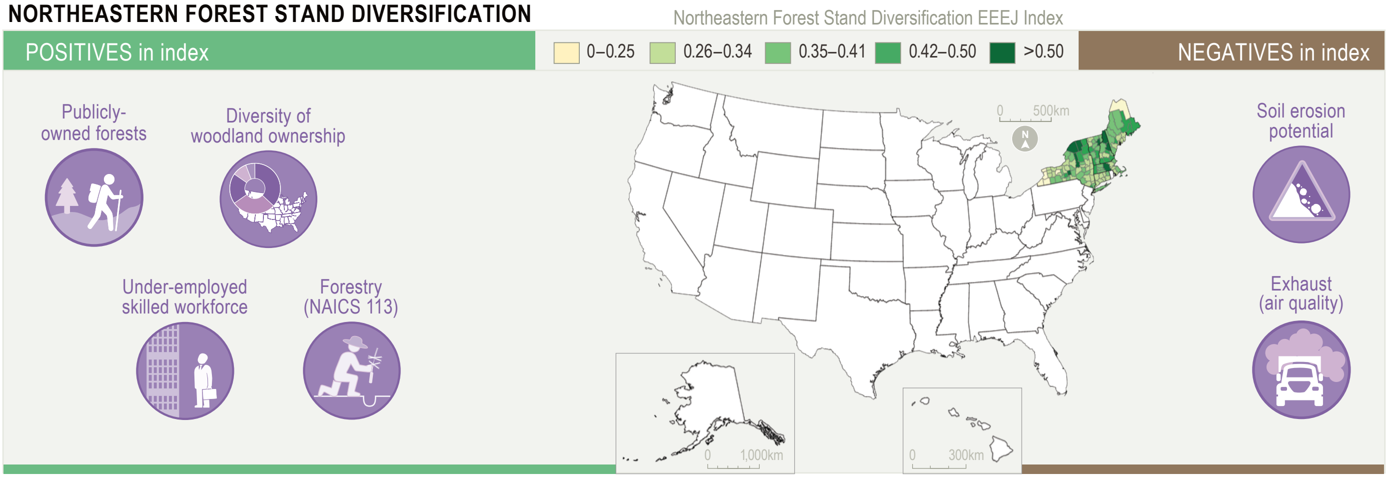


Figure 2-22 *Map of the EEEJ Index for northeastern forest-stand diversification, alongside each variable that contributed, positively or negatively, to the index. The index is normalized from 0 to 1; higher values represent a potentially greater opportunity for socioeconomic co-benefits, including re-employing skilled workforces and preserving publicly owned or minority-owned woodlands. Higher values also represent a smaller potential for negative environmental impacts from timber transportation, specifically traffic and health impacts from diesel-derived PM2.5, or potential short-term soil-erosion.*

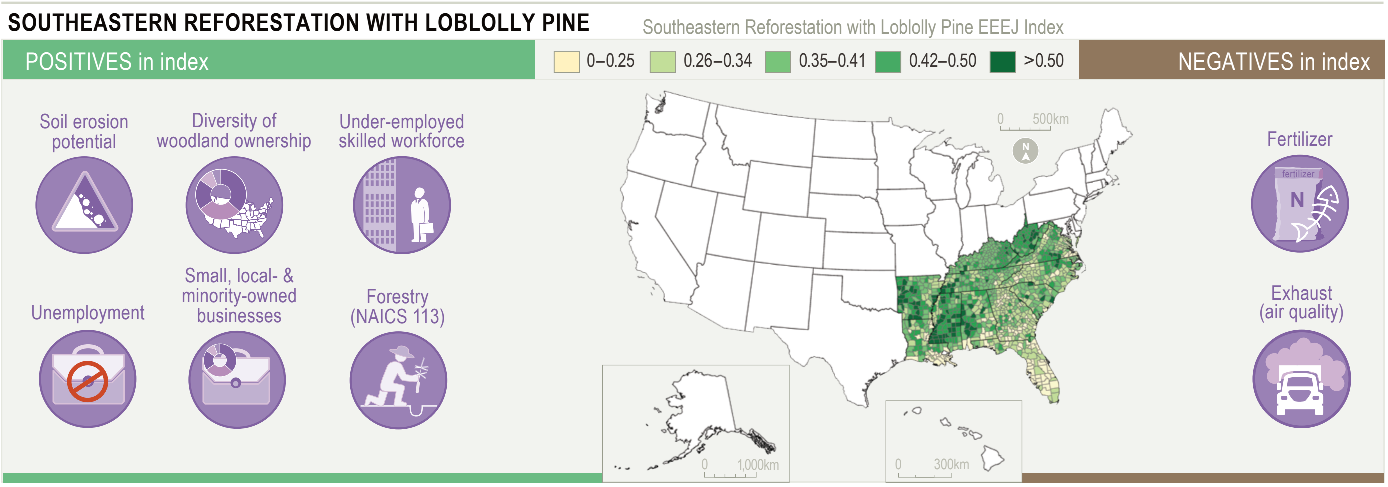


Figure 2-23. *Map of the EEEJ index for southeastern reforestation with Loblolly pine, alongside each variable that contributed, positively or negatively, to the index. The index is normalized from 0 to 1; higher values represent a potentially greater opportunity for socioeconomic co-benefits, including re-employing skilled workforces and reducing soil erosion. Higher values also represent a smaller potential for negative environmental impacts, specifically traffic and health impacts from timber transportation or water-quality risks from fertilizer runoff.*

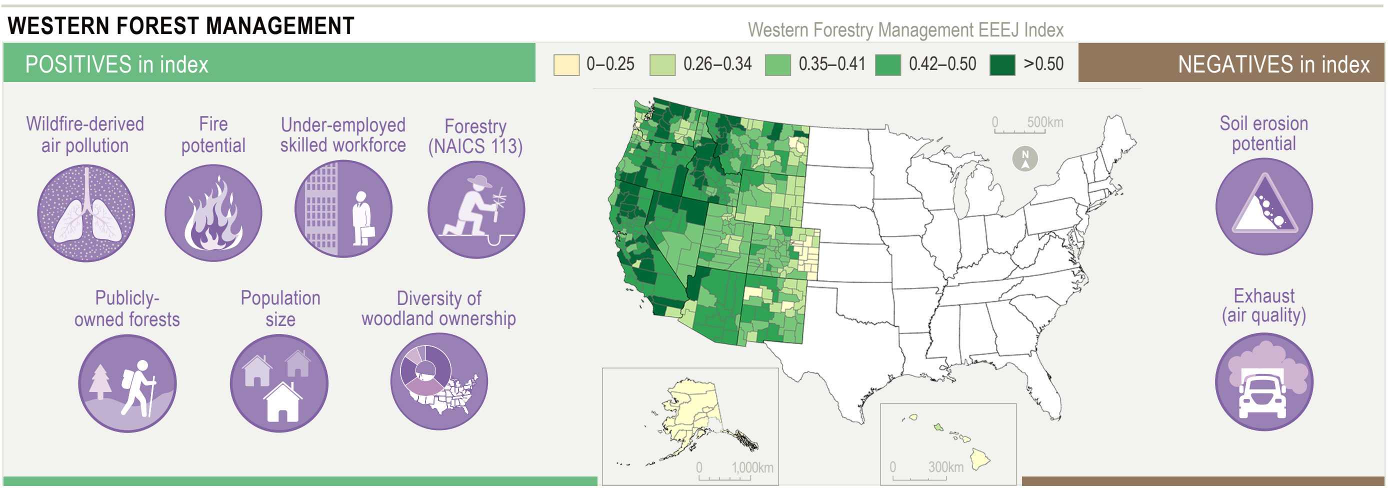


Figure 2-24. *Map of the EEEJ index for western-forest management, alongside each variable that contributed, positively or negatively, to the index. The index is normalized from 0 to 1; higher values represent a potentially greater opportunity for socioeconomic co-benefits, including reducing risk to people and property from wildfires and generally preserving public-benefitting land. Higher values also represent a smaller potential for negative environmental impacts, specifically traffic and health impacts from timber transportation or short-term soil-erosion risks post-thinning.*

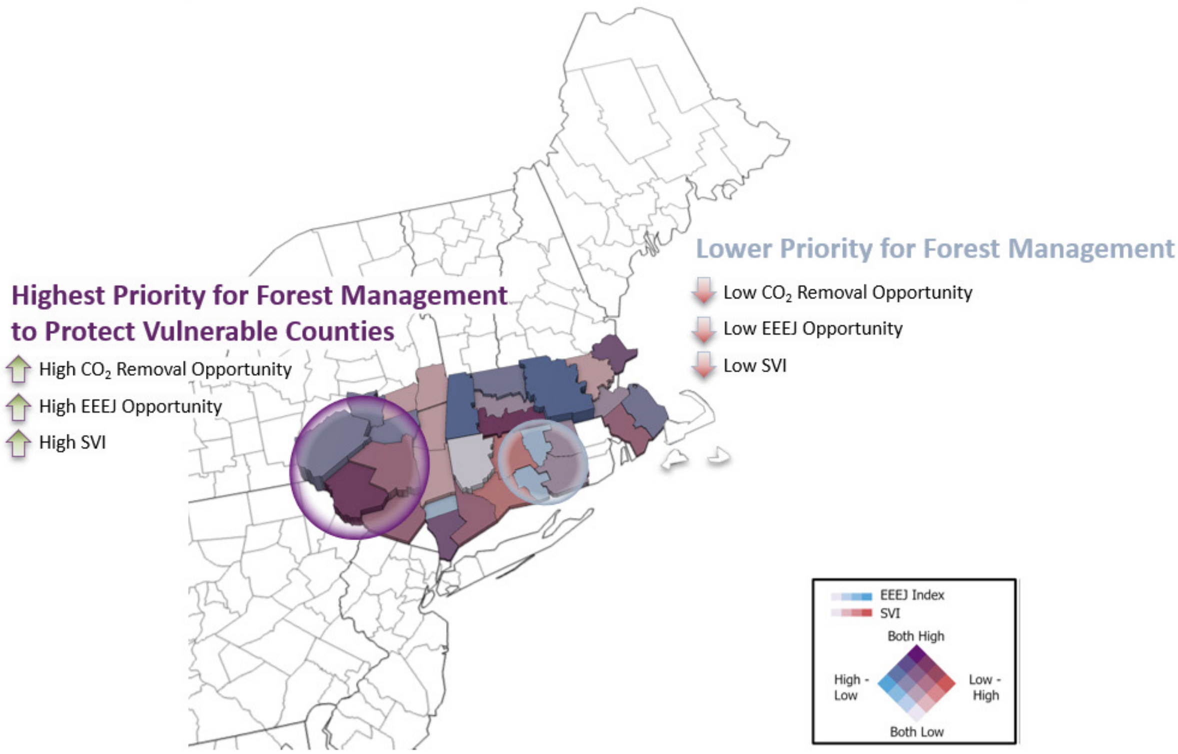


Figure 2-25 *Map of EEEJ Index data (blue) and the CDC's Social Vulnerability Index (SVI) (red) for the United States in counties whose CO_2-removal costs were analyzed in this report. The height of counties in this map represents potential for CO_2 removal through forest-stand diversification, where taller counties have the greatest cumulative capacity for CO_2 removal through 2050. In this report, we categorized forest management as a "protective" CO_2-removal practice, which exhibits outsized potential for protecting people and property from forest disturbances (e.g., windstorms), and note that the key reason for these management practices not being implemented currently is lack of funding or capacity. Therefore, our premise is that if a county has high opportunity for co-benefits and high social vulnerability, then they may benefit from equity-enhanced outreach and funding for forest management practices that may increase public safety. Conversely, counties with high opportunity for co-benefits but low social vulnerability may similarly benefit from increased forest management but perhaps have a less urgent need for outreach, given that these counties are more likely to have secondary protective measures in place (e.g., resilient infrastructure or nearby access to emergency services).*

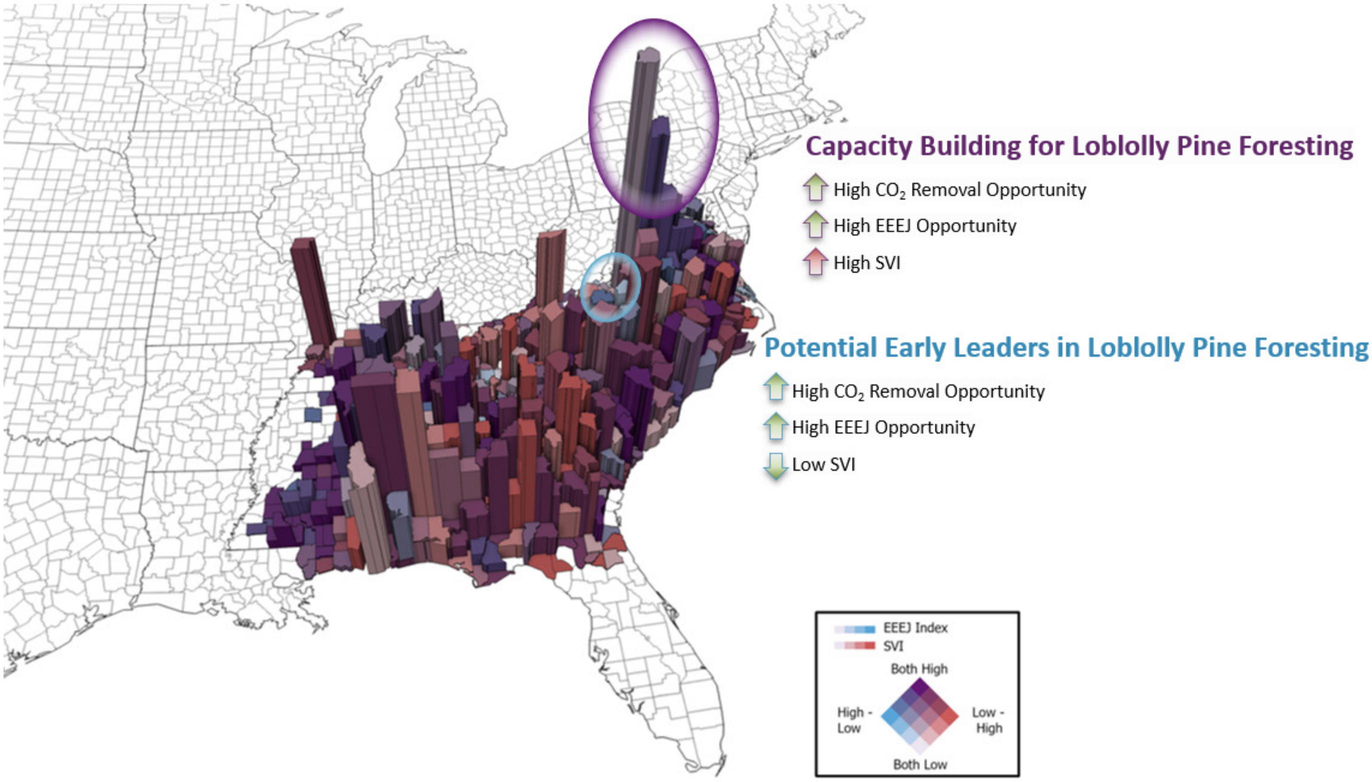


Figure 2-26. *Map of EEEJ Index data (blue) and the CDC's Social Vulnerability Index (SVI) (red) for the United States in counties whose CO_2-removal costs were analyzed in this report. The height of counties in this map represents potential for CO_2 removal through reforestation in with Loblolly pine, where taller counties have the greatest cumulative capacity for CO_2 removal through 2050. The map is annotated to reflect this report's premise around southeastern Loblolly pine reforestation as a collaborative CO_2-removal method: if a county has high opportunity for co-benefits and low social vulnerability, then they may be better poised to become early leaders in the practice with project developers. Similarly, counties with high opportunity for co-benefits but also high social vulnerability may benefit from investments in local capacity building to engage on the topic of Loblolly pine reforestation.*

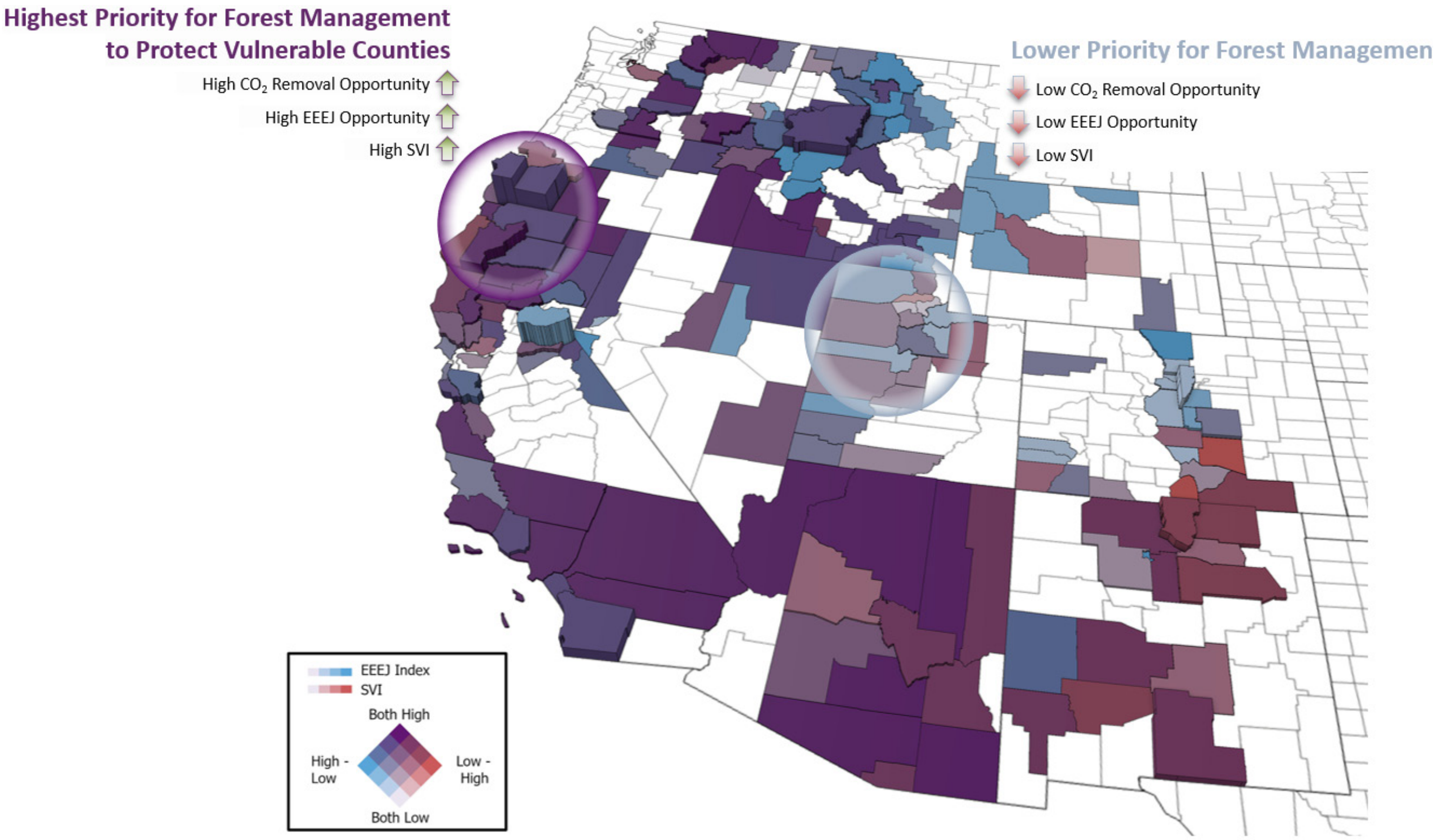


Figure 2-27 *Map of EEEJ Index data (blue) and the CDC's Social Vulnerability Index (SVI) (red) for the United States in counties whose CO_2-removal costs were analyzed in this report. The height of counties in this map represents potential for CO_2 removal through forest management for wildfire abatement, where taller counties have the greatest cumulative capacity for CO_2 removal through 2050. In this report, we categorized forest management as a protective CO_2-removal practice, which exhibits outsized potential for protection of people and property from forest disturbances (e.g., wildfires), and note that the key reason for these management practices not being implemented currently may be lack of funding or capacity. Therefore, our premise is that: if a county has high opportunity for co-benefits and high social vulnerability, then they may benefit from equity-enhanced outreach and funding for forest-management practices that may increase public safety. Conversely, counties with high opportunity for co-benefits but low social vulnerability may similarly benefit from increased forest management but perhaps have less urgent need for outreach, given that these counties are more likely to have secondary protective measures in place (e.g., resilient infrastructure or nearby access to emergency services).*

5. Conclusions

Forests remove and store CO_2 from the atmosphere, serving as living "DACS machines" powered through renewable solar energy, storage facilities that hold carbon in living plant tissues, and pipelines that transport carbon into forest soils. As we consider options for building new grey infrastructure to remove, pipe, and store CO_2, we should also remember that we already have full operational green CO_2-removal infrastructure across the United States.

Every year, we rely on forest DACS machinery to remove and store CO_2. Forests are a critical net sink for the Nation's carbon-accounting books. Yet, the future reliability of US forests as a net carbon sink is uncertain, and the efficiency at which they continue to remove carbon may decline. Every time we convert a forest to some other land use, we are decommissioning a fully operational DACS facility. Further, some (but certainly not all) of our forest DACS facilities need maintenance. Historical actions, such as widespread forest clearing, displacement of indigenous people who stewarded these forests, and historical policies (e.g., fire suppression in forests), have led to the forest landscape we see today. Stalled or decreased funding for forest management, research, and development are limiting our current and future capacity to maintain our forest DACS facilities [186, 187]. Just as our grey infrastructure requires service and upkeep, so does our green infrastructure.

In our analysis, we assessed forest-maintenance activities for selected US regions. We demonstrated that we have options to manage forests in ways that reduce the risks of widespread disturbances and increase the likelihood that our forests will be more resilient to these disturbances when they occur. Management also proactively prepares forests to "come back online" quickly after a disturbance disruption.

- In **Section 3.1**, we explored *how planting 2.1 million ha (5.2 million acres) of the southeast in 2025 could provide total CO_2 removals between 1.51 and 1.78 billion tonnes of CO_2e by 2050.* Planting high-density pine forests for restoration could remove 71.14 million tonnes of CO_2e per year at a price of $1.22/tonne CO_2e. Alternatively, planting low-density pine forests for commercial plantations on the same land base could remove 67.27 million tonnes of CO_2e per year while generating a net revenue of $13.80/tonne CO_2e.
- In **Section 3.2**, we explored *how applying fire-resilience forest management treatments to 0.48 million ha (1.19 million acres) of dry forests in the western United States may provide up to 16.21 million tonnes of cumulative CO_2e removal by 2050 by abating wildfire impacts on forest carbon.* If limited to a maximum cost of $200/tonne CO_2e, this target could be achieved at an average cost of $47/tonne and an annualized rate of 0.64 million tonnes of CO_2e removal between 2025 and 2050.
- In **Section 3.3**, we explored how *application of regeneration-focused silviculture prescriptions across 2.6 million ha (6.4 million acres) of hardwood forests of southern New England and southeastern New York could lead to net climate benefits of 67.84 million tonnes of CO_2e relative to passively managing forest with no future harvests.* This drawdown can be achieved while generating a net revenue of $37.46/tonne CO_2e through timber sales. We note, however, that this finding includes accounting for wood-product substitution for fossil-based energy and materials and assumed the continuation of extreme natural disturbances, such as drought, wind, and pest and disease outbreaks, in the region. When only accounting for carbon stored in forest-carbon pools and wood products, this management would lead to a cumulative loss of 241.38 million tonnes of CO_2e by 2050

We note that the total storage capacity of US forests includes carbon stored in wood products. This "off the land" carbon storage source held approximately 102.8 million tonnes of CO_2e in 2021 [9]. There are multiple novel and emerging technologies that engineer harvested wood into longer-lived wood products that have substitution benefits for more carbon-intensive products. These technologies include engineered CLT—which can replace building materials, such as concrete and steel, that have large carbon footprints—and wood biochar, which minimizes the decay of wood carbon and may have additional carbon-capture benefits depending on its application. Supporting the research and development of these emerging economies for wood products delivers large carbon benefits.

One limitation of our analysis is that we did not exhaustively explore the possibilities for other management options within the regions we assessed nor did we investigate all important forest regions of the United States in detail. Forests missing in this report include urban forests (Box 2-8), the massive boreal forests of Alaska (which include 9.9 million ha (24.5 million acres) of forest), and the biodiverse tropical forests of Hawai`i and other tropical territories. Forest-carbon accounting for Alaska and the tropical territories are routinely excluded from national carbon accounting, with the exception of the 2019 US Inventory of GHGs that included carbon removals and emissions from Alaska's interior forests [9, 188]. This is, in part, because the United States has limited funding (or no funding) for collecting forest-inventory data for most of these regions. We also did not include analysis that covered forest-management options for other areas of the country, such as the temperate rainforests that cover the Pacific Northwest (which have the Nation's highest standing stores of carbon), the deciduous northern woods of the Great Lakes region, the highly productive "bottomland" hardwood forests of the Gulf and Atlantic coastal plains and the Lower Mississippi River Valley, the expanse of mixed hardwood-pine forests from Illinois through Texas, the piney woods of East Texas, the swath of hardwood forests that run the spine of the Appalachian Mountains from Georgia to Maine, or the coniferous spruce-fir forests of northern New England. The exclusion of these areas from our analysis was not because they are not important to consider, and their exclusion only means that there is more untapped potential than we describe in this report and the United States has other opportunities for protecting, restoring, and managing the forests' DACS capabilities.

Some may argue that because of the dire threats facing our forests, such as wildfires and insect and pathogen outbreaks, we should not invest funding or resources into forests as part of the Nation's CO_2-removal strategies. Our analysis indicates otherwise. Just as is it critical to protect and maintain grey infrastructure that captures, transports, and store CO_2, our Nation's green infrastructure can be supported and maintained by including forest management as a central and complementary component to other CO_2-removal strategies.

Finally, we should not just expand our forest base and manage our forests to remove and store CO_2. We should also expand our forest base and manage our forest resources to ensure they continue providing the multitude of services they have always provided to humans: non-carbon-based climate benefits, such as cooling temperatures and regulating climate; cleaning our air and our water; providing habitat for wildlife and other food, fuel, timber, fiber, and sources of biodiversity for human communities; and offering immense cultural, aesthetic, recreational, and spiritual value.

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