Forest Carbon Study: The Impact of Alternative Land-Use Scenarios on Terrestrial Carbon Storage and Sequestration in Massachusetts

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Prepared by:

For Massachusetts Executive Office of Energy and Environmental Affairs

Acknowledgements

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Glossary

Acronyms

DCR – Massachusetts Department of Conservation and Recreation.

DOER – Massachusetts Department of Energy Resources.

EEA – Massachusetts Executive Office of Energy and Environmental Affairs.

GHG – greenhouse gas such as carbon dioxide (CO_2) that trap heat and cause average global air temperature to rise and long-term weather patterns to change.

LSR – Land Sector Report, a technical report produced in 2020 as part of the Massachusetts 2050 Decarbonization Roadmap Study

NWL – Natural and working lands, including forests, croplands, grasslands, freshwater and coastal wetlands, and urban and parks, forests, other open space.

MMTCO_2e – Million metric tons of carbon dioxide equivalent. This is a measure of how much greenhouse gas is emitted into or removed from the atmosphere. An emission of 1 MMTCO_2e is equivalent to burning 112,523,911 gallons of gasoline.

Key Terms

Carbon pool – a particular reservoir of carbon; usually a component of an ecosystem (e.g., forest soil carbon, wetland dead organic matter).

Carbon sequestration – the process of removing CO_2 from the atmosphere and storing it in a carbon pool, i.e., the removal of CO_2 via photosynthesis and storage in NWL ecosystem carbon pools.

Carbon sink – a source of net carbon sequestration i.e. a system that removes and stores more atmospheric carbon than it emits.

Carbon stock or storage – the sum of all carbon pools in a defined area and time span. **GHG flux** – the rate of greenhouse gas release into (+) or removal from (-) the atmosphere from a particular source or sink per unit of land area (e.g., tons of CO_2e per hectare per year).

Greenfield (solar, building) development – construction of buildings, solar photovoltaic facilities, and/or other hard infrastructure on undeveloped natural and working lands (NWL).

Hectare – a unit of area equal to 10,000 square meters or 2.47 acres.

Land Sector – the GHG emissions sector that covers GHG emissions and removals from natural and working lands (NWL), also known as Land Use, Land Use Change, and Forestry.

Mass timber – a family of engineered wood products formed by layering and bonding pieces of wood together and that can be used as structural elements in large buildings as an alternative to materials like steel or concrete.

Net emissions – the sum of all GHG fluxes within a defined period and scope (e.g., net forest land emissions).

Silviculture – the art and science of controlling the establishment, growth, composition, health, and quality of forests to meet the diverse needs and values of landowners and society such as wildlife habitat, timber, water resources, restoration, and recreation on a sustainable basis. (Source: US Forest Service).

Wood utilization – how we produce and use wood, i.e. the process of turning in forest wood/timber into wood products for human consumption (e.g., lumber, paper, Mass timber) and following these products through its end of life (e.g., disposal in landfill).

1. Executive Summary

1.1 Overview and Key Findings

The Commonwealth's Global Warming Solutions Act (GWSA), as amended in 2021, requires Massachusetts to achieve net zero greenhouse gas emissions (GHG) in 2050. The net zero requirement allows for up to 15% of 1990-level emissions to be "offset" by GHG removals, which includes carbon sequestration from natural and working lands (i.e., the land sector; for the purposes of this report, references to the land sector excludes agriculture). In the U.S., the land sector is net sink for GHGs, removing 14.5% of gross emissions (EPA 2023). In Massachusetts, the land sector currently removes approximately 11% of Massachusetts' gross annual GHG emissions, with forested land being the primary carbon sink, but the magnitude of future carbon sequestration and emissions will be affected by many natural processes and human activities that could make the land sector a source or a sink of atmospheric carbon. The purpose of this report (hereafter, the Forest Carbon Study), commissioned by the Massachusetts Executive Office of Energy and Environmental Affairs (EEA), is to quantify the effects of forest growth, natural disturbances, deforestation, reforestation, and active forest management, such as timber harvesting, on the state's land sector carbon budget, as well as assess the potential influence of these factors on forest composition, structure, and adaptation and resilience to climate change. While the results inform the directionality of forest-related policies particularly for their role in helping the Commonwealth achieve net zero emissions in and beyond 2050, the study did not model specific policies under consideration by EEA.

The study uses state-of-the-art modeling of alternative land-use scenarios and **finds that limiting forest loss to development, ensuring post-disturbance forest recovery, and reducing the emissions from timber harvest are the actions with the greatest potential to protect forest carbon stocks and support ongoing long-term net carbon removal.** More specifically:

- **The state's forests are expected to continue serving as a long-term net sink of atmospheric carbon,** removing on the order of 200-300 MMTCO_2e from 2020 to 2100. This is the equivalent of forests removing 3 to 4.5 years of Massachusetts' current statewide gross GHG emissions over the next 80 years. **However, this forest carbon sink is vulnerable to natural and human disturbances.**
- **Hurricanes pose the largest single threat to forest carbon, with high disturbance scenarios resulting in periods of weaker sequestration rates (~1-2 MMTCO_2e per year) or even net emissions** to the atmosphere (up to ~5 MMTCO_2e per year). Net sequestration rates are projected to recover within ten years, **assuming impacted forests are not converted to other land uses.**
- Under scenarios **with minimal natural disturbances, forest carbon sequestration rates in Massachusetts should persist at current rates of approximately 5 to 6 MMTCO_2e per year through mid-century**, after which they are expected to decline to less than 1 MMTCO_2e per year by 2100 due to forest aging.
- **If recent trends in land use continue to 2050, the emissions from development and harvesting would reduce net sequestration by 20% (averaging 1.2 MMTCO_2e per year) relative to a hypothetical scenario with forest growth but no land conversion, harvesting, or major disturbances.** Permanent forest loss for building and solar development would account for approximately half of this difference. The

remaining half is attributable to timber harvesting (accounting for carbon storage in wood products and landfills).

- **Less land-consumptive building and solar development practices could reduce carbon emissions from land conversion by up to two-thirds by 2050, while still achieving the Commonwealth's projected solar capacity needs**. A continuation of recent trends in building development is expected to result in 14.0 MMTCO_2e of emissions between 2020 and 2050 (0.5 MMTCO_2e per year), while solar development that follows siting patterns from 2010-2020 and grows to meet anticipated needs is expected to result in up to 13.5 MMTCO_2e (0.5 MMTCO_2e per year) by 2050. **More sprawl-oriented building development patterns could increase these emissions by up to 50%.** These potential changes in emissions would be even greater if accounting for the impacts of development on soil carbon, which was not examined in this study.
- Reforestation and tree-planting **could modestly increase carbon sequestration rates in 2050 by a maximum of 0.6 MMTCO_2e per year or a more achievable 0.1 to 0.3 MMTCO_2e per year.** Total carbon removal potential from expanding forest and tree cover is relatively small due to limited suitable land, with an upper bound of 6 MMTCO_2e by 2050 and 29 MMTCO_2e by 2100.
- **Forest management presents complex tradeoffs between mid- and late-century cumulative carbon removal, sequestration rates, and other forest attributes and benefits, with effects contingent on disturbance levels.** Management emphasizing local wood production could reduce in-state carbon sequestration through 2050 relative to a continuation of recent management practices, up to ~30 MMTCO_2e total through 2050 (averaging 1 MMTCO_2e annually) while producing more than 52 MMTCO_2e of additional wood products in the same time frame. The differences in annual sequestration become less significant by 2100, particularly with low disturbance levels.
- **Utilizing greater proportions of wood generated by harvesting, disturbances, and land clearing into durable products can reduce associated emissions, though these effects are only substantial with high levels of disturbance and salvage harvesting.** With minimal disturbances, these emissions reductions amount to ~5 MMTCO_2e by 2050 and ~13 MMTCO_2e by 2100. With high disturbance levels and salvage harvesting, these emissions could be reduced by 65 to 80 MMTCO_2e by 2050 and 90 to 135 MMTCO_2e by 2100.
- **Active forest management, including continuing conventional and climate-oriented silvicultural practices, can improve key indicators of forest resilience to climate change.** These practices, particularly the modeled climate-oriented prescriptions, help improve landscape-scale species and structural diversity values and increase regeneration opportunities for keystone tree species relative to reserves and untreated areas.

These key findings and the study approach are elaborated below (1.2 Summary of Methodology and 1.3 Summary of Results), including additional context and explanation of the rationale, nuances, and assumptions of the findings.

1.2 Summary of Methodology

The analyses presented here were conducted using a suite of spatially interactive ecosystem and land-use models. These models have been calibrated with and validated against empirical data and the results published previously in dozens of peer-reviewed articles. The model simulations are initialized using US Geological Survey land-cover maps and US Forest Service maps of forest tree species composition. Simulated ecosystem processes include species-specific tree establishment, growth, competition, senescence and disturbance-related mortality, and decomposition. Forest management is simulated using alternative silvicultural techniques, and the harvested carbon is tracked using a carbon allocation model. A cellular automata model simulates patterns of forest loss and gain. GHG fluxes from non-forest terrestrial carbon is estimated using a spatially explicit bookkeeping model, which utilizes static carbon density estimates for multiple land covers derived from an extensive literature review. Despite their important role as carbon stores, the study does not estimate stocks or fluxes of soil carbon; this is because of the high level of landscape heterogeneity in soil carbon and the scientific uncertainty regarding the belowground impacts of land use. In addition to investigating terrestrial carbon dynamics, this study also analyzes the outputs from the forest ecosystem model to assess outcomes for non-carbon forest attributes, including indicators of forests' adaptative capacity and resilience to climate change.

The study analyzes eight integrated land use and disturbance scenarios that bracket the upper and lower bounds of plausible forest management, ecological disturbances, and land cover changes. High levels of disturbance and high rates of development-driven land conversion were paired to represent a high-emission future while low levels of disturbance and rates of land conversion were paired to represent a low-emission future. The study also includes a counterfactual scenario—for comparative purposes only—that simulates continued forest growth without any major disturbances or future land use—i.e., no harvesting, reforestation, hurricanes, insect outbreaks, or building or solar development. All the scenarios are purely illustrative, intended for learning, and do not represent specific policies under consideration by the Commonwealth. Co-designed by the research team, staff at EEA, the Massachusetts Department of Conservation and Recreation (DCR), and a group of experts and stakeholders, the Integrated Scenarios envision four alternative future forest management regimes, each occurring under a high- and a low-emissions regime (Table E1). The scenarios explore forest management options that are frequently proposed to advance climate and conservation goals, including: improved "climate-oriented" silviculture practices, establishment of large forest reserves, and increased harvesting to meet more of Massachusetts' wood demand locally. These practices are overlaid onto dynamic landscapes with and without hurricanes, and differing levels of other ecological disturbances (such as insect outbreaks and blowdowns), deforestation for building and greenfield solar,[1] and reforestation and tree-planting. Simulations of forest dynamics and management scenarios span from 2020 to 2100, while simulations that include land cover change only span 2020 to 2050.

In addition to the eight Integrated Scenarios, the study includes a set of Focused Scenarios. These scenarios focus on specific drivers of forest land cover change and analyze their effects on future terrestrial carbon. These include scenarios depicting alternative rates and spatial distributions of new building and solar development, as well as alternative reforestation and tree planting scenarios. Similar to the Integrated Scenarios, we use counterfactual scenarios that omit key drivers to provide reference-cases against which land-use scenarios can be compared to isolate individual effects. For example, we simulated a counterfactual scenario that includes forest growth and minor natural disturbances but omits all land use (development or harvesting)

[1] Greenfield Solar refers to solar installation built in previously undeveloped land cover (i.e, forest, croplands, or grass/shrub)

and major disturbances (hurricanes or insect outbreaks), allowing us to determine the impacts of these drivers on carbon storage and sequestration.

***Table E1**. Eight Integrated disturbance and land-use scenarios codesigned with EEA, DCR, and a group of experts and informed stakeholders.*

	Forest Management Regimes			
	Recent Trends	*Reserves Emphasis*	*Local Wood Emphasis*	*Combined Emphasis*
Forest Harvest:	Current forestry practices and harvesting levels	Climate-oriented forestry, current harvest levels	Climate-oriented forestry, increased harvest levels to meet 20% of MA wood consumption	Climate-oriented forestry, increased harvest levels to meet 15% of MA wood consumption
Forest Reserves:	Current forest reserves	Expand forest reserves to 33% of forest land	Current forest reserves	Expand forest reserves to 20% of forest land
Land Cover Change & Ecological Disturbance Regimes: *High Ecological Disturbance* / *Uncoordinated Land Cover Change*	**Recent Trends Harvest + High Disturbance/ Development Scenario**	**Reserves Emphasis + High Disturbance/ Development Scenario**	**Local Wood + High Disturbance/ Development Scenario**	**Combined Emphasis + High Disturbance/ Development Scenario**
Land Cover Change & Ecological Disturbance Regimes: *Low Ecological Disturbances* / *Coordinated Land Cover Change*	**Recent Trends Harvest + Low Disturbance/ Development Scenario**	**Reserve Emphasis + Low Disturbance/ Development Scenario**	**Local Wood + Low Disturbance / Development Scenario**	**Combined Emphasis + Low Disturbance/ Development Scenario**
Wood Utilization:	Two variants for all scenarios: (a) *Recent trends wood utilization* (b) *Improved wood utilization*			

1.3 Summary of Results

The counterfactual scenario with no harvesting, development, or major disturbances estimates that the theoretical biophysical potential for Massachusetts' existing forests to sequester and store additional carbon between 2020 and 2050 in the absence of land conversion, harvesting, and major disturbances is 177.0 $MMTCO_2e$ (Figure E1). Since disturbances and land use will occur, this estimate is useful insofar as it defines the land system's theoretical maximum carbon uptake without major shifts in the system. When we include a continuation of recent trends in land use (i.e., development and timber harvesting) and non-hurricane disturbances, net carbon sequestration is 147.8 $MMTCO_2e$ between 2020 and 2050 (not shown in Figure E1 and not including reforestation or tree-planting).[2] The difference between the counterfactual and the recent trends in land use is 29.2 $MMTCO_2e$ by 2050—or an average of 1.0 $MMTCO_2e$ per year—and represents the additional theoretical net carbon sequestration. This constitutes a relatively modest potential increase over the current level of NWL annual carbon sequestration,

[2] Due to the inherent uncertainty in human development patterns, we did not simulate land cover change beyond 2050 and therefore cannot estimate impacts of a continuation of recent land use trends to 2100.

not nearly enough to fully offset the 14 $MMTCO_2e$ of allowable residual emissions in 2050 under the Massachusetts Net Zero emissions limit (EEA 2022).

The counterfactual scenario estimates that, without any major disturbances or harvesting, the rate of forest carbon sequestration would begin to decline after ~2060 and eventually reach a dynamic equilibrium by 2100 (Figure E2). The decline reflects the forests' reduced rate of growth and increased rate of tree mortality associated with the aging of the forest—i.e., increasing ecosystem respiration relative to gross primary production—and the absence of any new tree planting (Figure E2). The timing of this inflection in carbon accrual is based on our best understanding of the relevant ecological and physiological processes; however, estimates of all ecological dynamics occurring further into the future and further outside of observed forest conditions should be interpreted with greater skepticism.

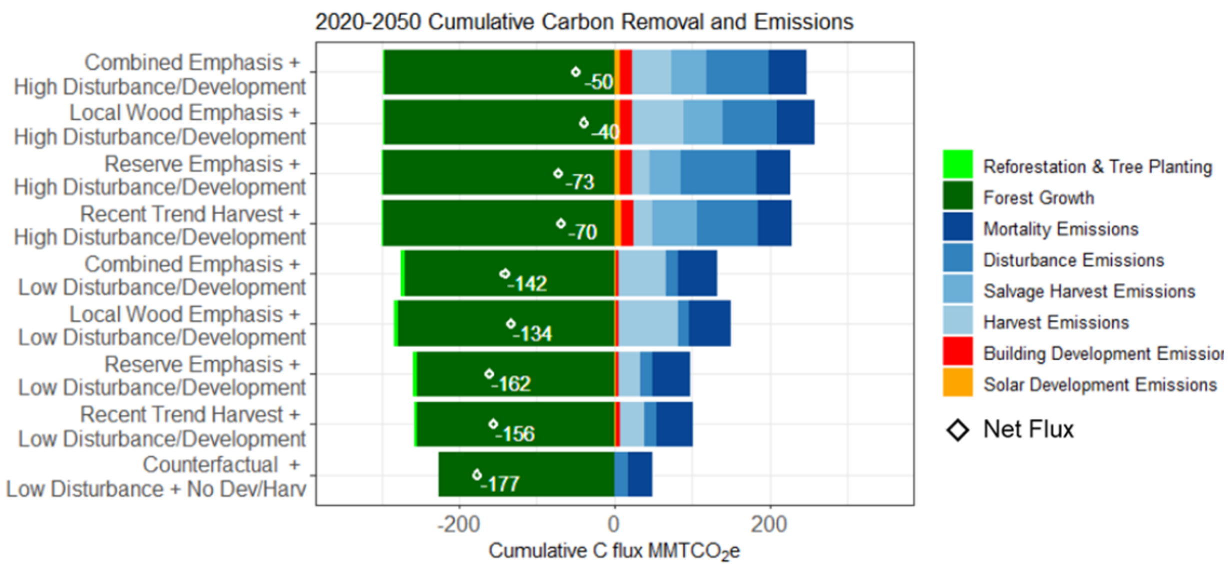

Figure E1. *Cumulative carbon removals and emissions from 2020 and 2050 for the eight Integrated Scenarios and a counterfactual scenario (no development or harvesting). Green bars to the left represent cumulative removals (i.e. sequestration), bars to the right represent cumulative emissions, and white diamonds show the cumulative net flux to the atmosphere. Carbon transfers between all simulated pools are accounted for, including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills. Note that the "High Disturbance" scenarios include a major hurricane in 2038 and much higher levels of building and solar development, which alter the trajectory of carbon accumulation.*

Of all the influences on land sector carbon that we examine, hurricanes are the single factor that poses the greatest risk (Figure E1). We use the simplifying assumption that the timing and storm track of future hurricanes would mirror the hurricanes observed during the 20th century. To account for anticipated effects of warming oceans on hurricane strength, we increased hurricane wind speeds by 8% above what was observed and applied them to the 21st century,100 years after they occurred—e.g., the Great Hurricane of 1938 was simulated to occur in 2038 and be 8% stronger (see year 2038 in Figure E2). Our analysis shows that these storms have the potential to flip the land sector from a sink to a source of atmospheric carbon in the short term (5-10 years post hurricane) (Figure E3). Salvage logging can mitigate some of the carbon losses associated with major disturbances, but salvage logging also can have ecological consequences and logistical challenges that should be considered. The hurricane-induced flip from carbon sink to source is temporary with recovery to a net carbon sink generally occurring within 10 years post hurricane so long as the forests are allowed to recover and continue to grow. However, the timing of future hurricanes has a large impact on the contribution of the land sector to the state's 2050 Net Zero emissions goal. For example, the impact of the modeled 2038 hurricane on net land sector emissions would shift if such a hurricane were to happen earlier or later.

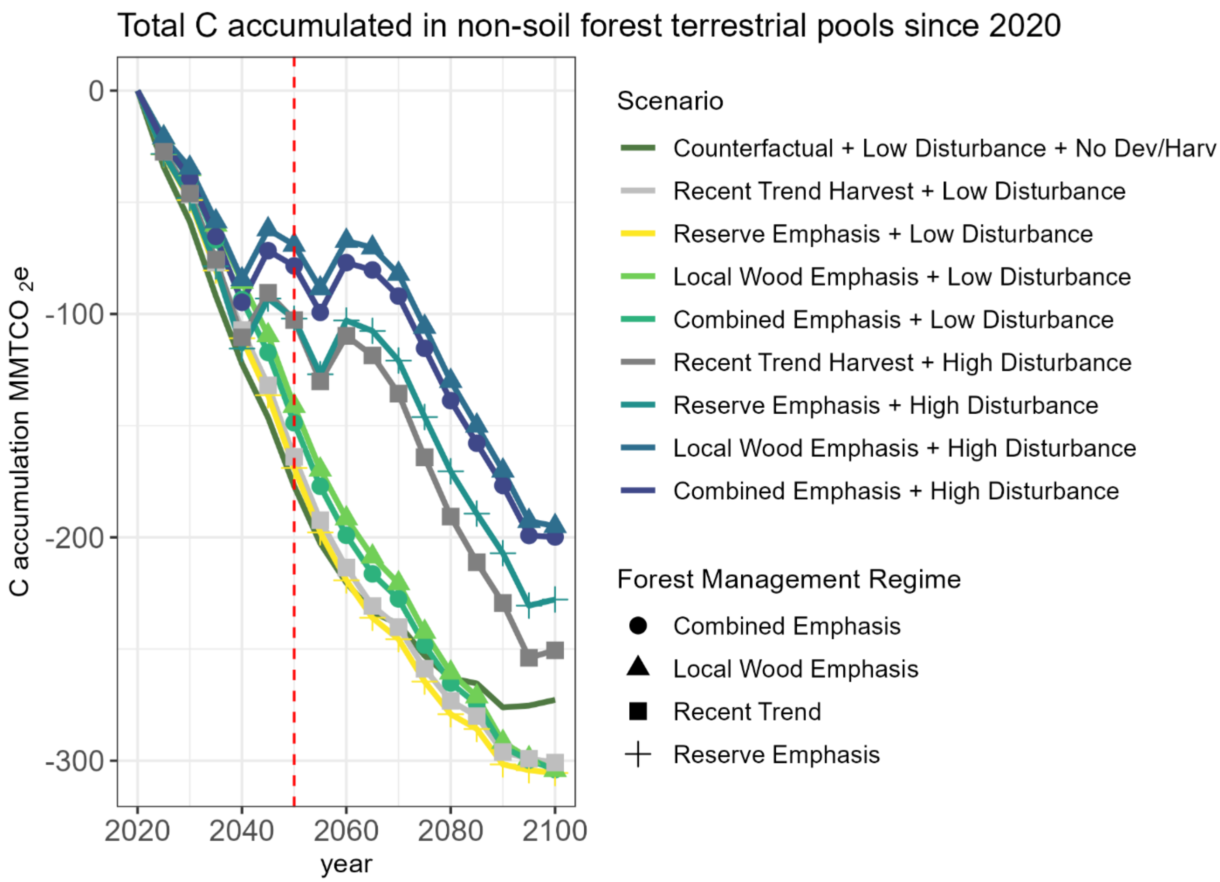

Figure E2. *Total accumulation of carbon from 2020 to 2100 in all non-soil carbon pools (including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills). Negative values indicate cumulative carbon removal from the atmosphere (i.e. cumulative negative emissions). For consistency across time, these results do not include the effects of development-driven land conversion because development was not simulated past 2050. Note that the "High Disturbance" scenarios include major hurricanes in 2038 and 2054. Red dash line indicates 2050, Massachusetts' net zero compliance year.*

Some of the Integrated Scenarios envision large increases in the area designated as forest reserves, characterized by passive management with no resource extraction or other vegetation manipulation. Currently, less than four percent of the state's forests are in a designated reserve. We explored the consequences of increasing reserve area to 20% and 33% of forest land. The location of new reserves was informed by the experts and stakeholders who weighed the importance of multiple environmental criteria, such as landscape connectivity, current carbon density, and species composition. The scenario with low disturbances and the largest increase in reserves resulted in the highest level of carbon stored among all scenarios considered (Figure E1); however, the -161.7 $MMTCO_2e$ in carbon accumulation compared to the scenario portraying a continuation of recent trends resulted in a quite modest difference (5.51 $MMTCO_2e$; just 3.5% higher by 2050). The small differences are because the Reserve Scenarios include an influential assumption that statewide annual harvest volume would remain unchanged by the new reserves; only the locations of harvests would change to accommodate the reserve area. By maintaining statewide harvest volumes, the scenarios attempt to control for the potential that harvesting "leaks" out-of-state beyond the baseline level observed in recent trends. The effect of this assumption is that Reserve Scenarios increase carbon density (amount of carbon stored per unit area) inside newly reserved areas and decrease carbon densities outside of reserves, with small net increase of statewide terrestrial carbon stocks. Any increase in reserve area to increase forest carbon stocks would need to consider how new reserves will affect harvest behavior outside of the reserves, in and outside of the Commonwealth. If leakage of harvesting is less than 100% – i.e., if new reserves result in less total harvest volume with a concurrent decrease in wood product demand – then these scenarios would underestimate the potential for forest reserves to increase carbon stores.

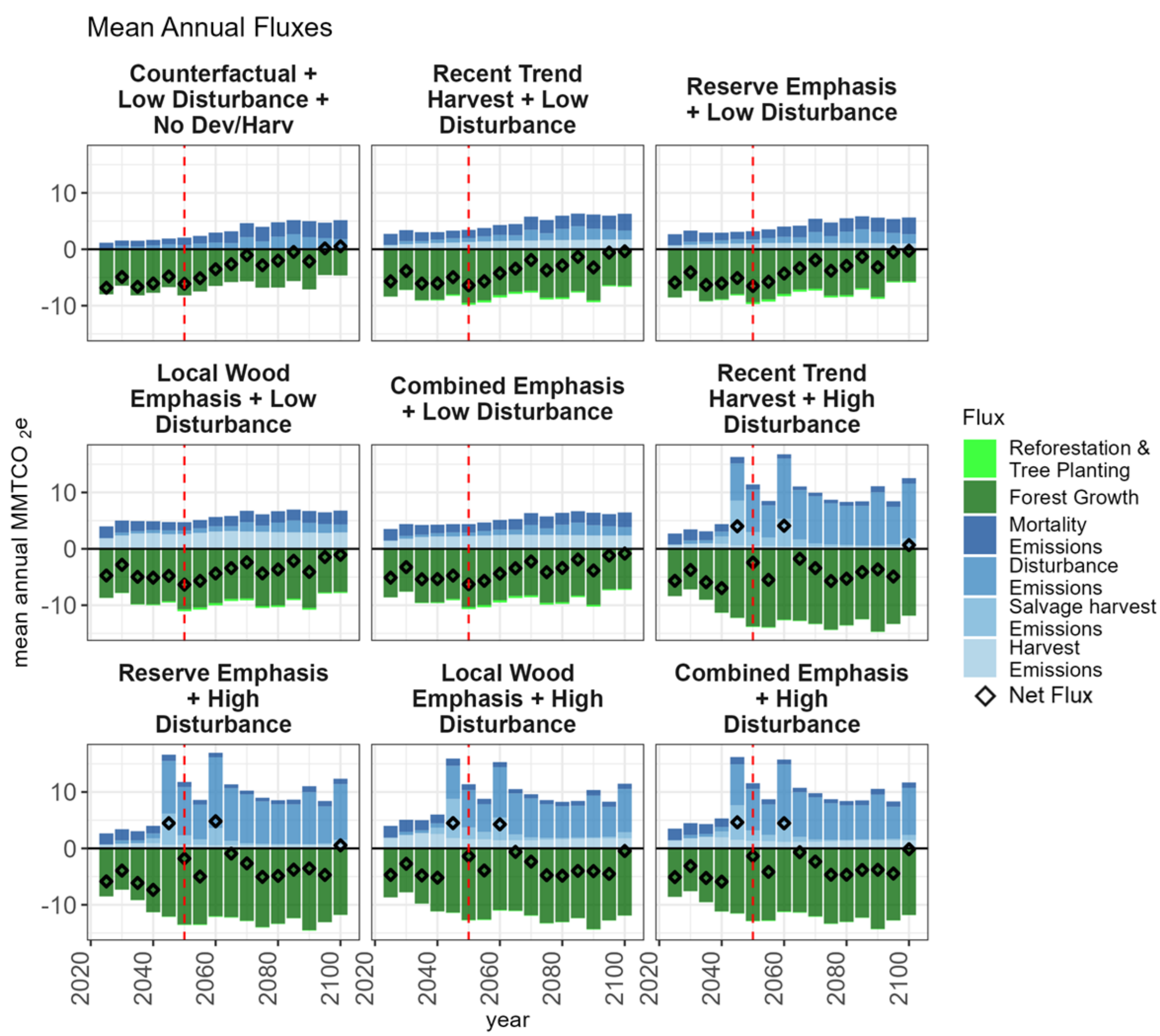

Figure E3. *Mean annual carbon fluxes to the atmosphere over 5-year timesteps from 2020 to 2100 for a counterfactual scenario (no development or harvesting) and the eight Integrated Scenarios. Green bars below zero represent carbon removals (i.e. sequestration), blue bars above zero represent emissions, and black diamonds show the net flux to the atmosphere (i.e. the annualized difference between sequestration and emissions in a timestep). For consistency across time, these results do not include the effects of development-driven land conversion because development was not simulated past 2050. Note that the "High Disturbance" scenarios include major hurricanes in 2038 and 2054. Red dash line indicates 2050, Massachusetts' net zero compliance year.*

While some stakeholders emphasized the need for more reserves, others suggested that Massachusetts' residents should take greater responsibility for their consumption of wood products by harvesting more wood locally, which could lower lifecycle emissions and create economic demand for commercial forestry in Massachusetts versus conversion of working forests to another land use. Currently, harvest volumes in the state account for approximately 7% of the volume of wood products it consumes annually, and only 5% of the lumber.[3] The Local Wood scenario increases annual harvest volume to ~20% of current consumption levels. Even at this higher rate of harvest, Massachusetts forest remain a net carbon sink throughout the century. In the near term (i.e. until at least 2050), increasing harvesting to this level would reduce cumulative carbon storage relative to a Recent Trends scenario by 22.2 to 30.2 $MMTCO_2e$, for low and high disturbance regimes respectively. This focus on timber production results in approximately 63.4 and 52.8 $MMTCO_2e$ of additional wood products by 2050, for low and high disturbance regimes respectively. After approximately 75 years, carbon accrual in the Local Wood scenario is similar to Recent Trends with low disturbances but lags behind with high disturbances through the end of the century. Our analyses also show that carbon emissions associated with commercial forestry can be reduced by improving wood utilization. We simulated improvements such as a shift to producing and using more long-term products (e.g., mass timber or wood insulation) and more efficient logging and milling practices. These practices have the potential to reduce harvesting emissions by 5%-14% by 2050 and 10%-12% by 2100.

Active forest management, where it was simulated, was found to have a strong influence on forest composition, structure, and successional trajectories. Well-planned and executed silviculture can help ensure the continuity of structural conditions across the landscape over time, including young and old forest habitat and facilitate the adaptability of natural communities to a changing climate. Modeling of practices designed to reflect a recent trends-based harvest regime resulted in a more even distribution of forest structural conditions and patch sizes, increased regeneration and recruitment of keystone tree species in natural communities and helped perpetuate those communities over time relative to untreated areas. Scenarios designed to reflect climate-oriented silvicultural practices included additional elements, such as stand improvement and other early interventions in stand development (not normally practiced in Massachusetts due to cost); adjustments to the patch size, intensity, and frequency of harvests; and ecologically informed, ecoregion-specific species removal and retention priorities. Modeling results from areas receiving climate-oriented silvicultural treatments tended to have enhanced species and structural richness and diversity, climate adaptability, and increased values of some indicators of resilience relative to areas treated with recent trends-based silviculture and areas reserved from harvest.

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[3] Note that these estimates refer to the equivalent wood and fiber volume, not the actual source of the wood used in-state.

In addition to the effects of natural disturbances and forest management, the study examines alternative scenarios of forest loss and other land cover changes due to new building and solar energy development. By 2050, more compact building development patterns could reduce emissions and foregone sequestration from 14.0 to 4.7 MMTCO_2e, assuming greenfield development at one third the rate observed from 2000-2020. In contrast, sprawl-oriented building development could lead to emissions of 28.0 MMTCO_2e, assuming greenfield development rates twice those observed from 2000-2020. Emissions and forgone sequestration associated with new greenfield solar development to achieve the Commonwealth's projected solar capacity needs in 2050 (i.e., approximately 27 GW_{AC}, depending on the availability of other sources of clean energy generation and the level of demand management that can be achieved) range from 3.4 to 13.6 MMTCO_2e, depending on whether siting patterns follow conservation-based criteria or those observed from 2010 to 2020, and on assumptions about the level of solar production capacity per unit land area.[4] Actual emissions and emissions reductions can be expected to be greater when the effects of development on soil carbon are included.

Reforestation and tree planting are frequently recommended natural climate solutions, but face several challenges, including land availability constraints, slow initial rates of carbon accrual, and ensuring tree survivorship in the face of climate change, herbivory, invasive species, and other stressors. We examined the biophysical potential for reforestation and tree planting but did not assess social or economic constraints on implementation. We focused on reforestation in riparian areas, marginal agricultural lands, and other open space, as well as tree planting in developed areas, including parks and rights-of-way. In sum, active reforestation and tree planting are expected to have relatively small total carbon removal benefits, of 1.3 to 6.4 MMTCO_2e by 2050, and 5.3 to 29.5 MMTCO_2e by 2100, with >90% of that derived from reforestation. Sequestration rates would initially increase only modestly, though could reach 0.1 to 0.6 MMTCO_2e by 2050 before slowly declining later in the century. These ranges represent baseline and additional reforestation and tree planting occurring on 10% to 50% of suitable land by 2050.

Overall, the study estimates that the land sector will remain a significant carbon sink for many decades, irrespective of the land-use or disturbance scenario considered. However, the magnitude of the sink varies significantly among scenarios. Hurricanes are the largest single driver of variation—average net carbon sequestration in 2050 is approximately 58.0 MMTCO_2e among the scenarios that include hurricanes and 148.4 MMTCO_2e among scenarios without hurricanes (Figure E1). The impact of land use on the state's terrestrial carbon sink is smaller but also significant and, importantly, can be shaped by policies. Assuming similar natural disturbances and land cover change, the difference between the least and most impactful forest management scenarios spans more than 25 MMTCO_2e by 2050, reflecting an increase harvesting to supply more of the state's wood demand locally, though this range shrinks to 5 MMTCO_2e by 2100. The building development scenarios' impacts on carbon sequestration and storage span a range of 23.2 MMTCO_2e by 2050, the solar development scenarios span a range of just over 10 MMTCO_2e, and reforestation scenarios span a range of 4.95 MMTCO_2e by 2050 and 23.4 MMTCO_2e by 2100. This study's detailed findings can help policymakers in the Commonwealth understand the potential role of the land sector in achieving the state's climate mitigation goals under alternative disturbance, land-use, and management scenarios.

[4] Energy production from solar photovoltaic sources in lieu of fossil fuel-based sources does contribute to emissions reduction in the power sector, which is not examined in this report.

2. Introduction

The following technical report describes a series of analyses designed to help policymakers in the Commonwealth of Massachusetts understand the potential for terrestrial carbon to influence the state's climate mitigation and adaptation goals under alternative disturbance, land-use, and management scenarios. This study builds on the 2020 Land Sector Report (LSR) (Thompson et al. 2020) produced as part of the Massachusetts 2050 Decarbonization Roadmap Study (EEA 2020). The original LSR examined five scenarios that envisioned varying amounts of timber harvesting and greenfield building development. Under these scenarios, total carbon accumulation in forests and wood products was estimated to range from 176.79 to 185.25 $MMTCO_2e$ between 2020 and 2050 (averaging 5.89 to 6.18 $MMTCO_2e$/yr), between 36.3 and 42.6 $MMTCO_2e$ (1.2 to 1.4 $MMTCO_2e$/yr) less than a counterfactual scenario with no land use at all. While this analysis was useful for the Decarbonization Roadmap Study, it lacked much variation among scenarios and did not incorporate several important drivers of forest carbon dynamics in the state, such as hurricanes and greenfield solar development. The current study includes these drivers and assesses a wider range of alternative scenarios to explore how much certain activities and policy drivers could increase forest carbon sequestration rates and storage levels in the Commonwealth, while accounting for natural processes, ecological disturbances, and climate change, and without sacrificing forest ecosystem health.

The Commonwealth's Global Warming Solutions Act (GWSA), as amended,[5] requires the state to achieve net zero greenhouse gas (GHG) emissions in 2050. The net zero requirement allows for up to 15% of 1990-level emissions to be offset by GHG removals, which includes carbon sequestration from natural and working lands. As a leader among states, the Commonwealth will need to consider many difficult questions regarding the role of the land sector in their net zero policy, including how to set goals for terrestrial carbon in the face of irreducible uncertainties, how to account for the risk of future land based emissions and variation in future sequestration rates, and how to balance carbon sequestration rates, long-term carbon storage, and other forest ecosystems services and priorities (e.g., Cohen et al. 2021). Given these questions, a thorough understanding of the opportunity and the uncertainties is required (Gifford 2020).

The potential for future natural disturbances to influence terrestrial carbon dynamics is an important source of uncertainty (Seidl et al. 2017) that was not considered in the original LSR. Here we expand on the LSR to also consider the impacts of forest insects and hurricanes, which are two of the disturbances posing the greatest risks to Massachusetts' forests (Lovett et al. 2016; Boose, Chamberlin, and Foster 2001). These disturbances both have a history of causing major tree mortality events in Massachusetts and are expected to increase in severity due to climate change (Tumber-Dávila et al. 2024). In addition to the direct impacts on forests from major disturbances, this report also examines the potential for post-disturbance salvage logging to alter disturbance-related emissions.

As compared to the LSR, this study includes additional comparisons of modeled approaches to forest management. The silvicultural prescriptions developed for the LSR to reflect current harvesting practices are used here with minor modifications. Additional prescriptions have been developed to reflect 'climate-smart forestry' or 'climate-oriented forestry.' These prescriptions attempt to balance aspects of providing resilience (Holling 1973; Ferrare et al. 2019) and

[5] An Act to Create a Next Generation Roadmap for Massachusetts Climate Policy, Mass. Acts 2021, c. 8, §§ 1-12, amended the GWSA along with other relevant portions of the general laws.

adaptive capacity (Swanston et al. 2016) of forests to climate change and recognizing social responsibility (Littlefield and D'Amato 2022) by implementing ecological forestry (Palik et al. 2021). Adaptive capacity is the ability of a resource to accommodate or cope with potential climate change effects with minimal disruption. Adaptation strategies include resistance, transition, and resilience; the latter of which is focused on increasing the capacity of a forest to absorb changes, resisting damage and stress, and recover quickly while maintaining relationships between its components. When these practices are implemented silviculturally they can generate wood products locally, reducing the need to import wood, help to sustain rural jobs, and avoid the effects of leakage from consumption of wood products. The suite of prescriptions also reflects regional ecological setting (western, central, and eastern Massachusetts), and focus on regenerating and retaining species well-suited to the broad ecological and expected future climate conditions. They aim to maintain stands at densities that would support vigorous growth and resistance to stressors and provide a variety of age classes and structural conditions to emulate conditions found in unmanaged reserves.

In addition to examining the effects of changing harvest practices, this study evaluates the potential for increasing total harvest volume so that Massachusetts' forests provide a greater proportion of the wood consumed in the state. Currently, Massachusetts only produces approximately 7% of the wood it consumes annually, and only 5% of the lumber consumption (Littlefield et al. 2024). Demand for new construction over the next 30 years has been estimated to drive an increase in building square footage by 23%, primarily in the residential sector (EEA 2022) and the construction of new buildings, including the manufacturing of building materials, make up 11% of the global greenhouse gas emissions (Puettmann et al., 2021). However, changing building materials from traditional materials (e.g., steel, concrete, fiberglass, imported lumber) to new timber products (e.g., wood fiber insulation, mass timber) has the potential to mitigate some of these emissions (Oliver et al. 2014; Puettmann et al. 2021). Therefore, increasing the production of traditional and mass timber products from local wood has the potential to reduce lifecycle emissions from the building sector. Here we examine some of the consequences of producing more timber, including the potential for new mass timber markets and improved harvesting efficiencies to affect overall carbon emissions.

The study also examines the potential for a broad expansion of forest reserves, where no harvesting or other intensive land uses would be permitted. Currently, just 3.3% of the state is protected in forest reserves (Foster et al. 2023). Increasing reserve area may allow for greater protection of carbon stocks (Erb et al. 2018; Nunery and Keeton 2010), some types of biodiversity and forest structural conditions (Faison et al. 2023) and allow for the eventual creation of old forest structure (Albrich et al. 2021), which is lacking in the state (Oswalt et al 2019; D'Amato 2006). However, the development of new forest reserves without a concomitant reduction in wood consumption threatens to shift harvesting outside of the state (i.e., leakage) without any real impact on harvesting related emissions (Gifford 2020). To guard against that possibility, in the increased reserve scenarios explored here, the total in-state harvest volumes were held constant–i.e., harvesting was redistributed outside of the reserve areas.

Reforestation and tree planting are also frequently advocated as important natural climate solutions (Domke et al. 2020) and promoted in the Commonwealth's Clean Energy and Climate Plans, Resilient Lands Initiative, and Healthy Soils Action Plan. Expanding the area of tree cover has the potential to increase total terrestrial carbon stocks. However, there are many challenges with reforestation and tree planting (Kirschbaum et al. 2024), including finding areas suitable for long-term forest development and siting tree species that are well adapted to current and future climate conditions. This study examines the potential for planting in developed areas, such as street and park trees as well as reforestation of greater acreages in riparian and other eligible sites.

While the original LSR examined the impacts of permanent forest loss to terrestrial carbon, it only assessed two scenarios of housing and other building development and did not include any analysis of new renewable energy development. Here we expand on the LSR to include divergent building development scenarios that range from a reduction (one-third) to an increase (doubling) of recent greenfield development rates. We also investigate the potential impacts of greenfield solar development, a growing driver of land cover change and deforestation in Massachusetts. Indeed, from 2010 to 2020 nearly 8,000 acres of solar development occurred in the state, with 60% of that occurring within forests (Manion et al. 2023). The pace of solar development is poised to increase substantially as the state seeks to achieve upwards of 27 GW_{AC} of solar generation capacity, as projected by the Massachusetts 2050 Decarbonization Roadmap Study. Here we analyze the land carbon impacts of several pathways to achieving that goal. Like the LSR, this report uses a spatial bookkeeping approach to quantifying carbon within non-forest land cover classes; here, we improve on the LSR by conducting a more thorough literature review and meta-analysis of the carbon density coefficients used for those land covers.

This study also evaluates some of the potential tradeoffs and synergies between carbon and forest resilience and adaptive capacity to climate change under different assumptions and silvicultural approaches. Massachusetts' aboveground live tree carbon density and forest stocking on forest land are among the highest in the northeastern United States; while its diversity of forest structural conditions is among the lowest (USDA Forest Service, 2024). Forests provide more ecosystem services than just carbon (e.g., habitat, clean water, wood), and there are a variety of silvicultural interventions that could provide for long-term maintenance of forest cover and potentially strengthen the harvested wood product carbon sink, while also reducing vulnerability and increasing resilience to climate change. Within the constraints of the model and study, a suite of metrics was identified at a variety of scales to help assess local- and landscape-scale structural complexity of and species composition.

For several aspects of the study, we expanded the temporal horizon to better understand longer-term dynamics of terrestrial carbon. Whereas the LSR simulated landscape dynamics to 2050, we now include model runs out to 2100 to better estimate the impacts of natural disturbances and harvest regimes. This is an important addition because forest systems change slowly over long timeframes and the ecosystem response to land use and disturbance is often not fully realized for many decades after the fact. Because land cover change (i.e., building and solar development) is thought to be particularly difficult to characterize in the future, we did not simulate those activities beyond 2050. As such, throughout the report, estimates from simulations of land cover change are given only to 2050, whereas estimates for disturbance and harvesting are given at both 2050 and 2100.

3. Methods

3.1 Study Framework

We integrated several modeling approaches to estimate potential future changes in landscape conditions and carbon cycling under alternative disturbance and land-use change scenarios. Forest growth, timber harvesting, and ecological disturbance are simulated using the mechanistic forest landscape model, LANDIS-II/PnET, which is described in detail below. Using the outputs from LANDIS, we coupled permanent changes in land cover (e.g., building and solar development, reforestation) simulated using Dinamica EGO, a cellular automata model, and wood utilization (e.g., new wood product markets) using a harvested wood products model that tracks carbon through the production, use, discard, and decay phases of wood use (Figure 1). Individual models are described in detail below. The LANDIS simulations use 5-year time steps. The models include several small-scale stochastic components (e.g., windfall, development placement) that stabilize to their average when measured at landscape scales. For this reason, we did not run multiple replicates of the simulations. Large scale stochastic processes, like hurricanes, can produce significant variation between simulations. Below (section 3.4) we explain our approach for representing one plausible realization of these processes.

The effects of forest disturbance and land use land cover change on forest carbon was modeled in the context of two groups of scenarios:

(1) Integrated Scenarios where multiple drivers of forest change are integrated to describe trajectories of landscape change that would logically emerge from different sets of assumptions. Integrated Scenarios are not forecasts or predictions; instead, they are a way to explore hypothetical futures that are plausible and based on internally consistent assumptions (Thompson et al. 2012). These scenarios were co-designed with the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) and invited stakeholders and subject matter experts.

(2) Focus Scenarios where individual drivers of forest land use and land-cover change are examined in isolation, with other factors held constant. These scenarios are designed to better understand the specific impacts of alternative building development, solar development, and reforestation scenarios on terrestrial carbon, as well as the individual effects of a continuation of recent trends in land cover change and in harvesting.

In addition to the Integrated and Focused Scenarios, we simulate a Counterfactual (no development, hurricanes, or harvest) scenario. This counterfactual scenario is used to estimate the maximum theoretical biophysical potential of Massachusetts' current forests to sequester and store carbon, assuming continued forest growth in absence of any land use or large disturbances. Of course, disturbances and land use will occur and, therefore, the rate of carbon accumulation in this scenario is not achievable and is not a realistic policy option; however, this scenario is a useful baseline for estimating the impact of disturbance and land use simulated in the other scenarios.

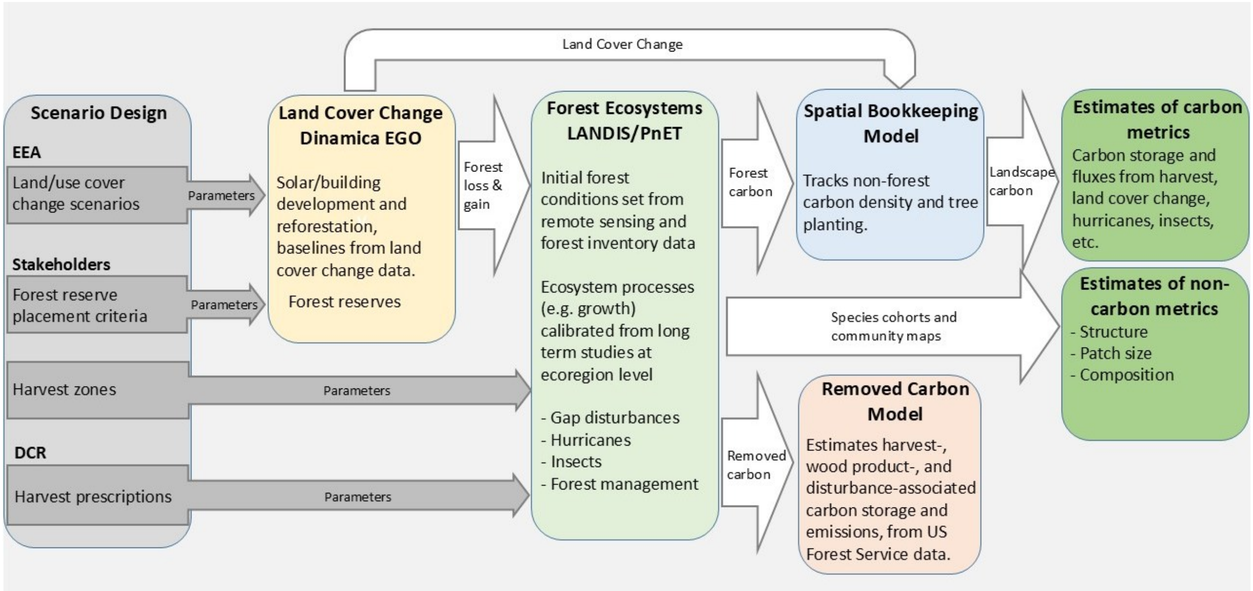

Figure 1. *Overarching analytical process including linkages between models and inputs. The Scenario Design box (gray) represents the co-design of scenarios, led by EEA and involving stakeholders, the research team, and DCR. The Land cover Change box (yellow) includes the land cover change model, which uses parameters co-designed with EEA and stakeholders to simulate transitions in land cover and reserves. The Forest Ecosystems box (light green) represents the mechanistic model that simulates forest growth, competition, disturbance, and forest management. The Spatial Bookkeeping box (blue) represents the spatial bookkeeping methods that applied the non-forest carbon metrics to the landscape. The Removed Carbon box (orange) represents the harvested wood product and downed wood models to account for carbon removed from the live forest carbon pool by harvesting or disturbance. The final two boxes (green) represent the carbon and non-carbon outcomes from the scenarios.*

Several stakeholders and subject matter experts were engaged in the creation of land management scenarios for this study and more specifically in the process of designing the new reserve and harvesting aspects of the scenarios. The EEA invited stakeholders and experts from around the state with expertise in—and diverse perspectives on—forest management and conservation to engage with the project team and design of aspects of the forest management scenarios. EEA and the research team held three different stakeholder meetings with check-in points between these meetings. An initial meeting was held to introduce the participants to the project and the many different aspects of the landscape being simulated. A second meeting was held to get feedback on which aspects of forest management and conservation are most important for designing new reserves/designated areas of passive forest management and applying new climate-oriented active forest management techniques within the study framework. A final meeting was held to get feedback on initial scenario results.

Throughout all the meetings, participants offered feedback on different aspects of the scenarios, including simulating improved wood utilization (see **Error! Reference source not found.**), increasing forest disturbance, and the importance of non-carbon forest benefits that should also be incorporated into the results. This stakeholder-informed process helped shape the forest management assumptions within the eight integrated scenarios that explore the range of impacts from varying levels of disturbance and land use (Table 1).

***Table 1**. The eight integrated land use scenarios use in this study, co-designed by the Massachusetts Executive Office of Energy and Environmental Affairs and stakeholders and subject matter experts.*

		Forest Management Regimes			
		Recent Trends	*Reserves Emphasis*	*Local Wood Emphasis*	*Combined Emphasis*
	Forest Harvest:	Current forestry practices and harvesting levels	Climate-oriented forestry, current harvest levels	Climate-oriented forestry, increased harvest levels to meet 20% of MA wood consumption	Climate-oriented forestry, increased harvest levels to meet 15% of MA wood consumption
	Forest Reserves:	Current forest reserves	Expand forest reserves to 33% of forest land	Current forest reserves	Expand forest reserves to 20% of forest land
Land Cover Change & Ecological Disturbance Regimes	*High Ecological Disturbance* *Uncoordinated Land Cover Change*	**Recent Trends Harvest + High Disturbance/ Development Scenario**	**Reserves Emphasis + High Disturbance/ Development Scenario**	**Local Wood + High Disturbance/ Development Scenario**	**Combined Emphasis + High Disturbance/ Development Scenario**
	Low Ecological Disturbances *Coordinated Land Cover Change*	**Recent Trends Harvest + Low Disturbance/ Development Scenario**	**Reserve Emphasis + Low Disturbance/ Development Scenario**	**Local Wood + Low Disturbance / Development Scenario**	**Combined Emphasis + Low Disturbance/ Development Scenario**
	Wood Utilization:	Two variants for all scenarios: (a) *Recent trends wood utilization* (b) *Improved wood utilization*			

3.2 Study Area

The study area was the 20,900 km^2 (8,070 mi^2) land area of Massachusetts, including the mainland, islands, and inland water bodies. We used the 2020 Land Change Monitoring, Assessment, and Projection (LCMAP) v1.3 (USGS Earth Resources Observation and Science (EROS) Center 2022) 30m resolution land cover map to represent the current landscape conditions. LCMAP consists of 7 primary land cover classes in Massachusetts. In this study, we modified the forest class using the LCMAP secondary class by reclassifying all pixels classed as wetland primary and tree cover secondary as forest to ensure forested wetlands were captured in our simulation of forests. Thus, the wetland land cover class in this study refers only to non-forested wetlands. We then further augmented the land cover map with spatial data on the location of reserve areas and greenfield solar development (further explained in sections 3.5 and 3.7). In the resulting map (Figure 2), forest is the dominant cover class and spans 57.2% of the study area. Developed land is the next largest land cover class (24.9%) and, while it is dispersed throughout the Commonwealth, is most prevalent and dense around the Boston, Worcester, and Springfield metro regions.

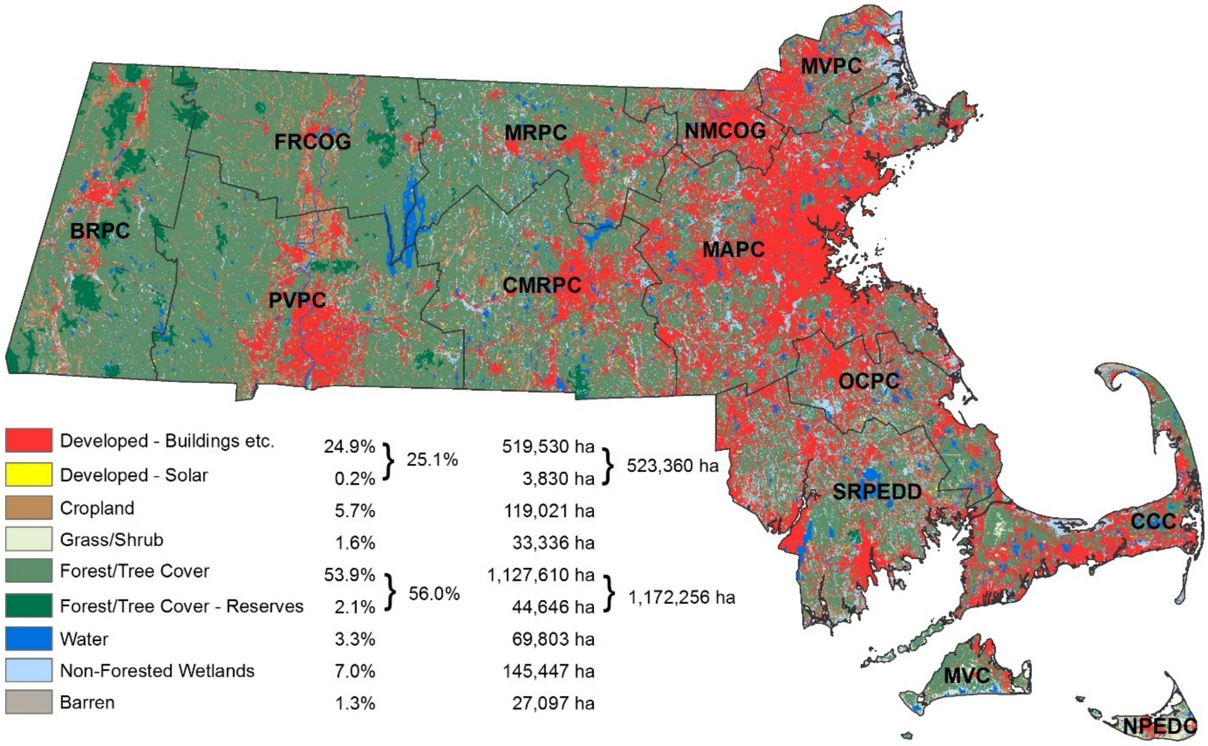

***Figure 2**. Study area showing LCMAP land cover in 2020 along with Regional Planning Area (RPA) sub-regions.*

3.3 Simulation of Forest Ecosystem Dynamics

The LANDIS-II cellular forest modeling framework was used to simulate forest ecosystem processes (Scheller et al. 2007). LANDIS-II is spatially interactive model designed to estimate future changes in tree species-by-age specific carbon stocks as they are affected by multiple processes, including: forest growth and succession, partial and stand-replacing disturbances, seed source proximity, and climatic and edaphic gradients on ecosystem distributions. The model has been widely used to research the potential impacts of timber harvest, land use, and climate change on temperate forest carbon dynamics (see www.landis-ii.org/publications). The Harvard Forest research team has calibrated and validated the modeling framework for use in Massachusetts and New England (Thompson et al. 2011; Duveneck and Thompson 2017; Liang et al. 2018; Graham MacLean et al. 2021; Liang et al. 2023).

Within the simulation framework, LANDIS is coupled to the PnET ecophysiology model, which was used to simulate tree establishment, tree species competition and succession, and growth rates (De Bruijn et al. 2014). The model produces species-by-age-specific maps of aboveground carbon at each timestep and tracks species-cohort biomass with the Output Biomass Community extension. LANDIS/PnET estimates carbon as a function of net primary production and heterotrophic respiration, which are sensitive to tree species traits, edaphic conditions, climate, and CO_2. Edaphic and climatic parameters vary spatially in Massachusetts based on EPA Level IV ecoregions ("EPA Ecoregions Level III and IV,"), and climatic conditions also vary temporally. We used the Soil Survey Geographic (SSURGO) database for Massachusetts to estimate edaphic conditions (e.g., soil water-holding capacity) (Soil Survey Staff, NRCS 2023; Thompson et al. 2011). We further parsed the EPA Level IV ecoregions by

SSURGO soil types, resulting in 86 unique LANDIS ecoregions. Future climatic conditions follow the IPCC's Representative Concentration Pathway 8.5 and was projected by the Community Climate System Model (CCSM4) Global Circulation Model (GCM) and obtained from the USGS GeoDataPortal (Stoner et al. 2013). We shifted from the Hadley Global Environment Model v2 (HADGE) GCM, which was used in the LSR, to the CCSM4 GCM. The CCSM4 GCM produces comparatively less extreme changes to temperature and precipitation, though we continue to use the RCP 8.5 scenario, and therefore maintain the same CO_2 levels as in the LSR. This was done to be consistent with the climate projections used in the MA Climate Change Assessment, and to use a regional temperature and precipitation projection that is closer to the median among all RCP 8.5 GCMs. The CCSM4 GCM still represents a high degree of change relative to all RCP projections, but not quite as high as the HADGE estimates used in the LSR.

We defined the initial forest extent using the 2020 LCMAP and within the forest class we characterize the forest conditions—in terms of tree species and age classes—primarily using the USFS's BIGMAP Forest imputation map (Wilson 2024).[6] BIGMAP assigns a USFS Forest Inventory and Analysis (FIA) plot (Burrill 2023) to each 30-meter pixel based on the similarity of the pixels' spectral signatures derived from the Landsat archive. Therefore, for each 30-meter forest pixel in Massachusetts, there is an imputed FIA plot number with tree inventory data. In some areas mapped as forest by LCMAP, BIGMAP did not include information on forest condition, in these cases we used a previous forest imputation product also developed by the Forest Service (i.e., Duveneck et al. 2015). We used the tree data from each of the imputed inventory plots (all trees > 2.54 cm) to initialize LANDIS/PnET. Due to the computational intensity of simulating all forests in Massachusetts (spatially explicitly), a few modifications were made to allow for more reasonable LANDIS/PnET simulation times. For example, while the native spatial grain of BIGMAP is 30m, we resampled to 90m within the forest cover to lessen the computational costs, though the forest class was resampled back to 30m when reintegrated with the land cover change simulations. We simulated 32 of the most common tree species, which represent greater than 96% of all tree biomass in the state, according to MA FIA data from forested plots measured in 2015 or later. We converted the tree stem information in the inventory plots to the model's required tree-species-by-age-class cohorts using plot information on stand age, tree diameter, and tree height (see LSR and/or Thompson et al 2011 for more details on model initialization).

The initial forest composition nominally represents the year 2020 and is dominated by early- to mid-successional tree species such as red maple (*Acer rubrum; 18% of total tree biomass*), red oak (*Quercus rubra; 17%*), and white pine (*Pinus strobus; 15%*), with lesser amounts of late-successional, longer-lived species, including sugar maple (*A. saccharum; 7%)* and hemlock (*Tsuga canadensis; 6%*). See Appendix I Table A1 for initial species biomass for all 32 simulated species. Simulated forest growth was compared to FIA remeasurements from the same time period and locations, and, while there is some variability in growth patterns, the overall growth rates seen in LANDIS/PnET closely matched FIA growth from plot remeasurement data (Figure 3).

[6] We updated the initial forest condition from what was used in the LSR to allow for more contemporary plot measurements and finer spatial grain.

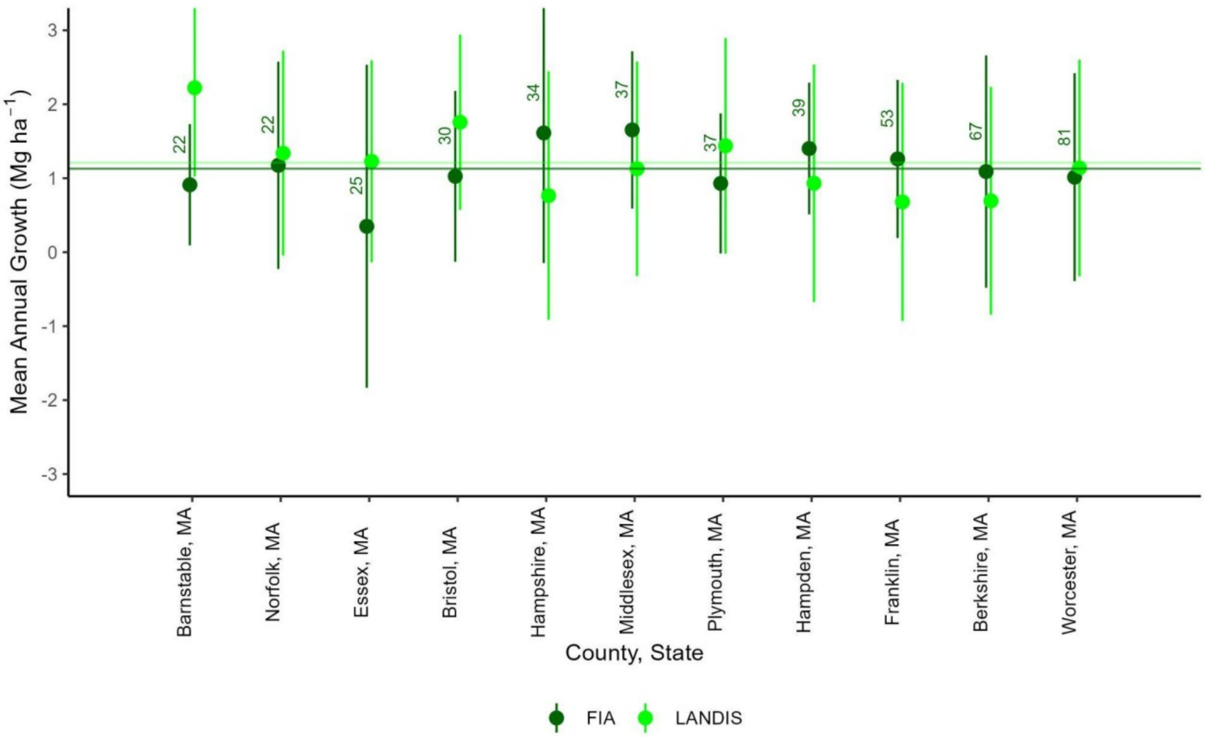

Figure 3. *Projected (LANDIS) and observed (FIA) mean annual growth by county. Dark green indicates FIA means, standard deviation, and plot N; light green indicates initial LANDIS pixel means and standard deviation. Horizontal lines are statewide means. 1.13 FIA versus 1.21 LANDIS Mg Ha yr-1.*

3.4 Simulating Forest Disturbance

Gap-Scale Disturbances

We simulated the impacts of a range of smaller disturbance based on the 1997-2020 Insect and Disease Detection Surveys (IDS) from the USDA Forest Service Forest Health Protection program (Forest Service 2022), which maps wind, insects, fire, and other gap scale disturbances (Tables 2A and 2B). We estimated the rate, patch size, and intensity of the "background disturbances" from the IDS 24-time series and used those data to parameterize the gap-scale (i.e., emulating the loss of a single canopy tree or a small cluster of individuals, sensu Oliver and Larson 1996) disturbance regime in LANDIS using the LandUse+ module (Thompson et al. 2021). In consultation with EEA and state experts, we developed and implemented two intensities of background disturbance, one a continuation of current disturbance rates as seen in the IDS (no change to area impacted or average intensity), and one that slightly increases the area disturbed and average intensity of disturbance to portray an increase in disturbance due to climate change (ramped gap-scale disturbance, Table 2a). Both background disturbance scenarios contain both light and severe disturbances (to emulate the range seen in the IDS), where light disturbances only cause mortality for 10% of the biomass per pixel, with the severe disturbance causing 90% mortality per pixel. In the continuation of current disturbance rates scenarios (i.e., low disturbance), 98% of the disturbed area has the light disturbance applied and the average total area affected does not change over time. In this version, we apply one randomly selected realization of the annual area disturbed from the IDS database to each future year (so area is not exactly the same each year but varies year to year within the range seen in IDS). In the high-disturbance scenarios, disturbed area affected by severe disturbance increases from 2% to 10% of all disturbed area by 2050 and then remains at 10% through the length of the simulation. This increases the intensity from 11% biomass removed on average in the disturbed area in 2020 to 18% on average between 2020 and 2050 and then remains static. Based on observed trends in the IDS dataset, we also increased total disturbed area by 1 ha per year from the current disturbance rates scenario until 2050 and then held the area static.

Hurricanes

In the high-disturbance scenarios, we simulated ten different hurricanes using the trajectory, extent, and wind speeds of hurricanes from the past century. Meteorological data for past hurricanes (1620-2020) is taken from (Boose, Chamberlin, and Foster 2001) (1620-1850) and the HURDAT2 database from the National Hurricane Center (1851-present) (Landsea and Beven 2015) to inform our hurricane projections, though we only explicitly simulated hurricanes that occurred between 1900-2000. Given we have no ability to predict the timing of future hurricanes, we set the timing of simulated hurricanes to occur exactly 100 years after they occurred in the previous century (e.g. the 1938 hurricane is simulated to occur in 2038). To project potential consequences of climate change on hurricane intensity, we increased the past hurricane wind speeds by 8% (Bender et al. 2010; Emanuel 2005; Knutson et al. 2010). We modeled spatial patterns of wind damage caused by the projected hurricanes using the HURRECON and EXPOS models which use information on hurricane track, maximum wind speed, and local topography to estimate wind damage from the hurricanes (Tumber-Dávila et al. 2024). We then applied the hurricane damage within LANDIS using the LandUse+ model (Thompson et al. 2016), which allows outputs from HURRICON to be used as inputs to LANDIS (Table 2A and 2C).

Insects

We explicitly simulated the potential impacts of two widely distributed and impactful invasive insects, the hemlock woolly adelgid (HWA) and emerald ash borer (EAB), which kill hemlock and ash trees, respectively (Table 2A). We chose to model these two invasive insects separately because their impact on the landscape is limited by the availability of host species. We assumed HWA is present throughout the state at the start of the simulation and EAB is present in municipalities where it had been observed by DCR (Department of Conservation and Recreation 2023). We then assumed EAB would spread to the rest of the ash-bearing forest in the state during the subsequent five years (Figure 4). Within the simulation, when a host species is affected by their insect pest, the majority of its non-structural carbon stores are depleted over a target number of years (10 for ash and 20 for hemlock), resulting in the death of the cohort. HWA and EAB disturbances were included in all of our integrated simulations.

Table 2. *Summary of forest disturbance characteristics.*

A. *Spatial distributions and forest impact for each disturbance type.*

Disturbance Type	Spatial Distribution	Forest Impacts
Gap-scale disturbances (e.g. wind, fire, disease)	Severe disturbance occurs on 2% of the disturbed area, remaining 98% receives light disturbance.	Light disturbance = 10% biomass removed; severe disturbance=90% biomass removed. See Table 2B for patch statistics.
Ramped gap-scale disturbance (increase from climate change)	Severe disturbance increases from 2-10% of the landscape until 2050 then remains at 10%.	
Emerald ash borer	Spread to ash stands by 2025 following Figure 4	Significant ash mortality within 10 years
Hemlock woolly adelgid	Present in all hemlock stands in 2020	Significant hemlock mortality within 20 years
Hurricanes	20th Century hurricane tracks (Tumber-Dávila et al. 2024)	See Table 2C

B. *Disturbance parameter statistics for simulated gap-scale disturbances, based on aggregated patch statistics from 24 Insect and Disease Detection Survey data layers.*

Disturbance Parameter	Units	Mean	Std. Dev.	Minimum	Maximum
Annual disturbed patches	#/year	4,236	5,888		
Annual area disturbed	ha/year	43,553	64,032	1,652	291,652
	acres/ year	107,622	158,226	4,082	720,687

C. *Hurricane Disturbance. The expected tree species damage (in % biomass) for each enhanced Fujita (EF) class*

Enhanced Fujita Scale (wind speed, mph)	Species Group	Tree Mortality (%) by Age Range*		
		0-19	20-79	80-300
EF0 (65-85)	Hardwoods	5	5-10	10-15
	Conifers	5-10	10-20	20-30
EF1 (86-110)	Hardwoods	10-15	15-20	25-35
	Conifers	15-20	25-45	40-60
EF2 (111-135)	Hardwoods	15-20	30-40	75-85
	Conifers	15-25	40-60	90-100
EF3 (136-165)	Hardwoods	20-30	40-50	90-95
	Conifers	35-40	60-80	100
EF4 (166-200)	Hardwoods	100	100	100
	Conifers	100	100	100

** Range from least to most susceptible trees for each category based on age class, tree species, and life history.*

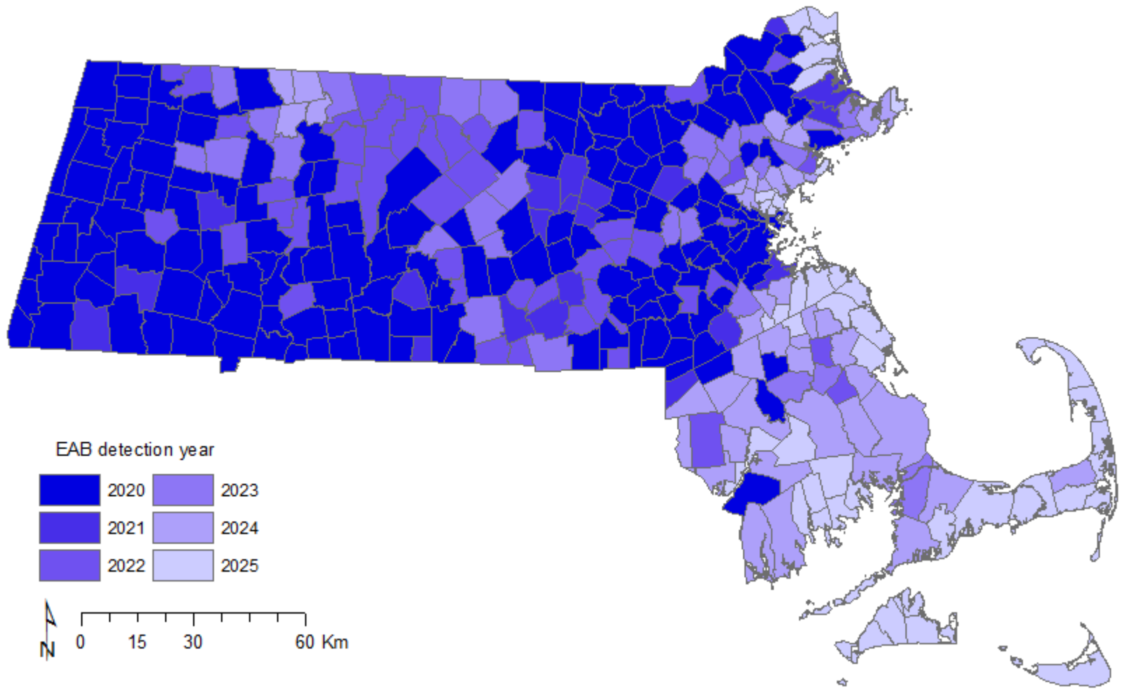

Figure 4. *Municipalities in Massachusetts where emerald ash borer (EAB) was present in 2020 (dark-purple), and the modeled statewide spread of EAB within the next five years.*

3.5 Simulating Forest Management

Active Forest Management

We modeled commercial timber harvesting in LANDIS/PnET using the Biomass Harvest v.4.6 module (Gustafson et al. 2000), which simulates user-defined harvest prescriptions that can vary over time and among uniquely parameterized and spatially explicit management areas. Harvest prescriptions determine the forest conditions necessary for a site to be eligible for a harvest, the size of the harvest, and the percent removed of each species-by-age cohort present on the stand if it is selected. After harvesting, the biomass removed during harvesting is recorded and used within the wood utilization model (see below), and, in subsequent timesteps, the LANDIS/PnET growth model responds to harvest-induced changes as removals alter the site's growing conditions (e.g., increased light availability and growing space). Specifics of the harvest prescriptions and harvest regimes are detailed below.

The scenarios used two distinct harvesting types, conventional forestry and climate-oriented forestry. The conventional forestry practices used within the Recent Trends harvest scenarios match the observed rates, spatial distribution, and silvicultural prescriptions documented in M.G.L. Ch. 132 Forest Cutting Plans (FCPs) from July 2001 through August 2017, as described in the LSR (see also Kittredge et al. 2017; McDonald et al. 2006). Staff from DCR used information reported in the FCPs about the silvicultural system (or lack thereof for high-grading and harvests classified as other), and professional judgement, to group reported harvests into silvicultural prescriptions. These prescriptions were generalized representations of broad silvicultural systems (even-aged and uneven-aged systems) with variations in treatments (thinning and overstory removals), removal intensities (low and high removal intensity variants of overstory removals), and harvest patch sizes (reflecting the distribution of parcel sizes in Massachusetts', with many more small forest ownerships than large). A complete definition of a model harvest prescription included the proportion of biomass removed within each combination of 29 modeled species and eight age classes, return intervals (if any), a minimum and maximum patch size, minimum age, and proportion of harvesting allocated to each prescription at each time step. The prescriptions were not further refined, calibrated, or validated due to time constraints. In most cases, removal intensities were based on expert opinion of state staff with a sound understanding of biomass stocking, species composition, and tree allometry since no information about removal intensity is available from the FCP database and only a subset of the modeled species was reported in the FCPs. The town where the primary landing (harvest loading site) was located on the cutting plan was used to group reported harvests and their area by regional planning agency (RPA) develop harvest rates and patch size distribution. See Appendix II and the LSR for further explanation of Recent Trends harvest methodology.

Climate-oriented/climate-smart forestry is defined here generally as practices that better meet both climate change adaptation and mitigation goals to enhance benefits from our forests now and into the future. The COF/CSF practices simulated in this study are based on input received from participants in the second stakeholder meeting, published reports (e.g., Mass Audubon 2024, NEFF 2023), and from DCR forestry staff. These represent some of the important strategies of COF/CSF for modeling purposes, but do not constitute a complete investigation of such practices, nor are they intended to define COF/CSF in the Commonwealth going forward.

Priority areas for active management employing COF/CSF practices were informed by the stakeholder process. Stakeholders and experts weighted multiple variables to quantify the landscape attributes best suited for active management. The research team averaged the weight among the participants and used these weights to guide simulated management. Their preferred variables included forest areas with more biomass in tree species expected to have lower climate change adaptability, in more hurricane-prone areas, and in areas with moderate amounts of biomass.

The COF/CSF prescriptions and their spatial allocation were developed by Department of State Parks and Recreation forestry staff and included input from the Division of Water Supply Protection and the Division of Fish and Wildlife. The modeled prescriptions incorporated features intended to improve outcomes in terms of metrics indicating forest resiliency, adaptive capacity, and ecosystem or community health (e.g. NRS-GTR-87-2, Ferrare et al., and Catanzaro et al. 2016). These metrics are described in more detail in Section 3.9. State staff designed these prescriptions to be used areas prioritized for active management with the intent of complementing forest dynamics in areas designated for passive management (see Passive Forest Management below). Harvest prescriptions were also adjusted across three broad regions of Massachusetts: west, central, and east. The goals of the silviculture were often focused on long term outcomes, rather than short-term carbon storage (e.g., deferring or treatments and/or reducing the intensity of removals). This included practices that provided structural conditions that complemented the surrounding landscape, or that adapted the scale and timing of treatments to natural disturbance regimes. Many of the most relevant and broadly applicable COF/CSF practices were included; however, it was not feasible to simulate all important silvicultural practices within the scope of this study (e.g., fire-based management, pitch pine-oak barrens-specific management, irregular uneven-age management, and assisted regeneration were not included).

Modeled COF/CSF included the following silvicultural systems and prescriptions:

- **Even-aged systems**: Emulating thinnings that create enough free growing space to keep trees vigorous, and disturbances intense enough and of a large enough area to regenerate diverse tree species.
  - *Thinning* – thin from below and retain the highest priority species, removing 33% of pre-harvest basal area (resulting in approximately 50% relative density).
  - *Overstory removal* – complete removal with variants retaining 12.5 BA (basal area in sq ft/acre; *Overstory removal* variant) and 0.5 TPA (trees per acre; *Overstory removal - intense* variant) of the species with the highest priority for retention.
- **Uneven-aged systems** - Emulating short- and long- return interval group selection-based uneven age management along a gradient of intensity.
  - *Group selection, 25-year rotation* – maximum age of 200 years, retaining 0.25 TPA of the largest trees of the species with highest priority for retention, with forest stand improvement and thinning to 62.5% relative density.
  - *Group selection, 40-year rotation* – maximum age of 120 years, retaining 4.00 TPA of the largest trees of species with highest priority for retention, with forest stand improvement and thinning to 75.0% relative density; 20% of area retained as unmanaged.
- ***Early simulation prescriptions*** – Implemented only during first 20 years of simulation.
  - *Targeted forest stand improvement* – critical interventions in young seedling and sapling cohorts to keep a diversity of regeneration present given pressures such as herbivory and drought.
  - Thin from below to 500 TPA of the species with the highest priority for retention for cohorts <25 years old plus the removal of 95% of hemlock and ash biomass.
  - *Targeted overstory removal* – Same as *Overstory removal retaining 12.5 BA* (described above) plus the removal of 95% of hemlock and ash biomass.

Summary statistics of biomass removed by age class for each prescription are shown in Table 3, while Appendix II includes further details on the development and limitations of COS/CSF prescriptions, as well as species removal and retention priorities, and harvest prescription entry requirements (i.e. forest conditions necessary for a stand to be eligible for each prescription).

On average, the COF/CSF prescriptions are less intense than the Recent Trends prescriptions, removing less than half (i.e., 41%) of the wood per hectare as did the conventional Recent Trends harvests. Therefore, the scenarios with COF/CSF needed to harvest more area per year to meet the volume targets specific to that scenario. For example, the Reserve Emphasis scenario aimed to remove the same amount of wood volume as the Recent Trends in harvesting scenario and to do so we doubled the total area harvested. For the Local Wood Emphasis scenario and the Combined Scenario (i.e., Local Wood & Reserves Emphasis), we needed to increase the area 460% and 343%, respectively, to meet the target wood volume. However, these increases alone were not enough to produce the target wood volume, so it was also necessary to substitute the Targeted Forest Stand Improvement prescription with the more intense Targeted OSR, to ensure enough area could be found to harvest in each year.

Table 3. *Summary statistics for the proportion of biomass removed by age class for each Climate oriented harvest prescription. Both "Targeted" prescriptions also include additional removal of 95% of hemlock and ash biomass.*

	Mean (std. dev.) % biomass removed by age class							
Prescriptions	0-10 yrs.	10-25 yrs.	25-50 yrs.	50-75 yrs.	75-100 yrs.	100-125 yrs.	125-175 yrs.	>175 yrs.
Thinning	55 (31)	47 (25)	29 (23)	21 (22)	20 (25)	16 (22)	16 (22)	17 (27)
Overstory removal	84 (23)	91 (14)	86 (13)	82 (18)	79 (23)	77 (23)	78 (25)	73 (31)
Overstory removal – intense	88 (23)	100 (0)	99 (1)	98 (11)	99 (2)	96 (15)	95 (18)	91 (26)
Group selection, 25-year rotation	35 (16)	35 (12)	28 (11)	24 (11)	24 (13)	22 (13)	24 (17)	23 (18)
Group selection, 40-year rotation	42 (10)	41 (6)	34 5)	33 (6)	34 (5)	32 (7)	33 (9)	31 (11)
Targeted forest stand improvement	64 (26)	64 (26)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Targeted overstory removal	84 (23)	91 (14)	86 (13)	82 (18)	79 (23)	77 (23)	78 (25)	73 (31)

Passive Forest Management (Reserves)

To better understand the potential for passive forest management to influence carbon stocks and forest conditions, some scenarios include expanded forest reserves. Here, we define reserves as "... tracts of any size and current condition, permanently protected from development, in which management is explicitly intended to allow natural processes to prevail with 'free will' and minimal human interference," consistent with the definition of "wildlands" in the recent report *Wildlands in New England* (Foster et al. 2023). While this may differ slightly from how the state defines reserves, in the context of this study's modelling approach it is equivalent to how state reserves are managed in practice. Accordingly, no harvesting (including salvage logging), building or solar development, or tree planting is simulated within reserves. This applies to the 3.4% of the state already in reserve status (taken from Foster et al 2023) and any newly created reserves as part of a scenario.

We sited new reserves within the scenarios based on feedback during the stakeholder process. Stakeholders and experts evaluated the importance of nine different variables by assigning each a weight with the constraint that the sum of their weights must be 100% (Table 4). The average of all the respondents' weights was then used to develop a Reserve Priority map (Figure 5). We applied a minimum allowable continuous patch size of 10 ha (~25 acres) for new reserve areas. The expanded reserves scenarios aimed to conserve approximately one-third of current forest land, which we achieved by prohibiting harvest or development on 399,138 ha. In addition to the stakeholder criteria, we stipulated that a minimum of 10% of forest area of each eco-region (west, central, east) must be in a reserve (Figure 6).

Table 4. *Reserve siting criteria and stakeholder weights (mean weight of all respondents).*

Variable	Weights
Core Forest	21.4%
Adjacency	14.3%
Connectivity	14.3%
Adaptation	14.3%
Structural Diversity	7.1%
Tree Diversity	7.1%
Stocks	7.1%
Sequestration	7.1%
Hurricane Prone	7.1%

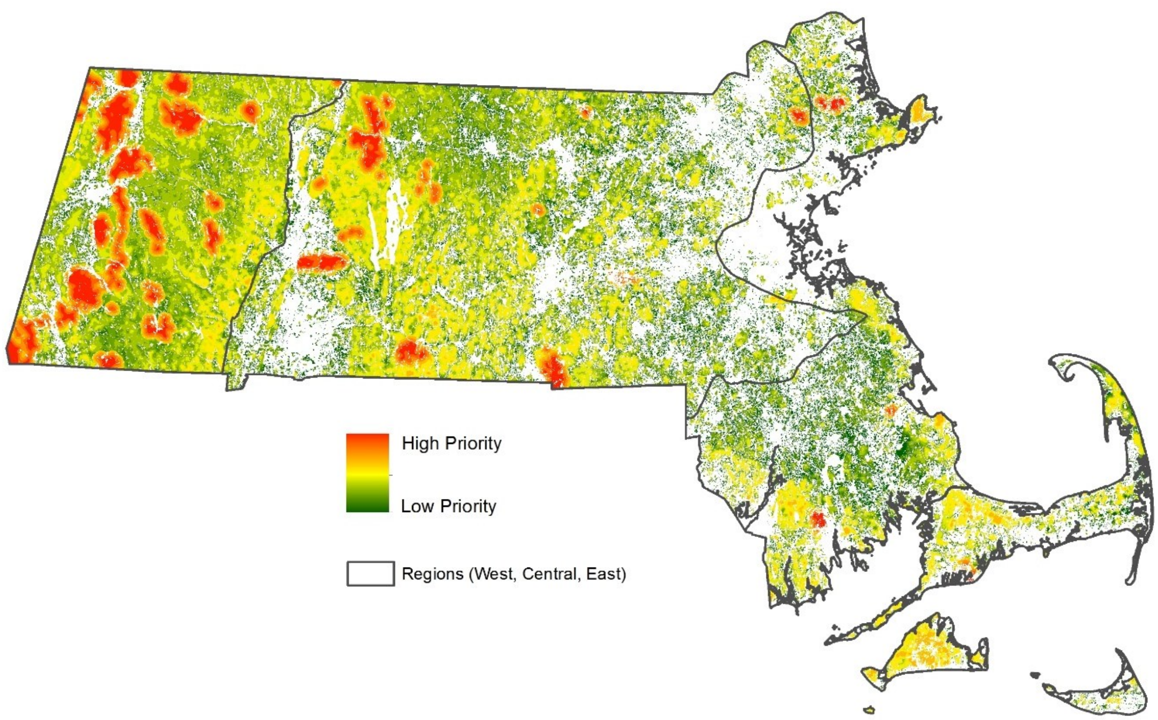

Figure 5. *Reserve priority map derived from the weights in Table 4 and smoothed for visual clarity using a 1km moving window. A minimum of 10% of forest area of each region (west, central, east) must be in a reserve.*

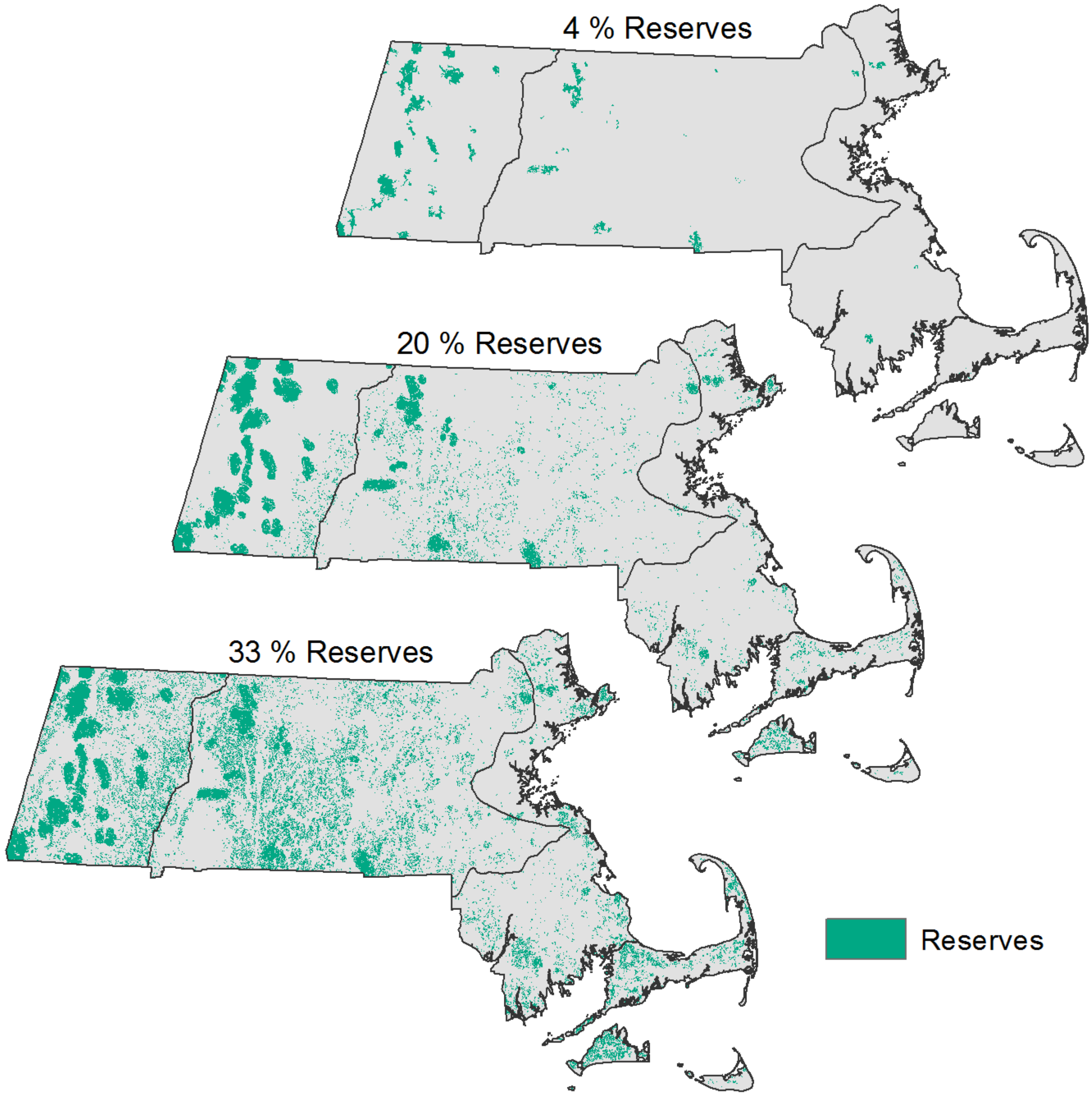

Figure 6. *Reserve areas analyzed within the Integrated Scenarios. The 4% in reserves represents the current condition. 33% forest in reserves was simulated in the Reserve Emphasis scenarios. The Reserves and Local Wood scenarios contain 20% forest reserves.*

3.6 Simulating Wood Utilization and Decay

To track carbon emissions and storage of wood no longer growing on the landscape (through mortality by forest processes, disturbance, or harvesting), we used a combination of published records of wood decay, harvesting efficiencies, and a newly parameterized Massachusetts variant of the state level Harvested Wood Products (HWP) model, HWP-C vR, used by the US Forest Service (based on the national level model, USFS HWP-C v1). The combination of these methods allowed us to estimate the fate of harvested wood carbon in several different pools, from in-forest downed wood and logging residue to wood products through their usable lifetime.

All coarse woody debris or downed wood that was produced during the simulation was modeled to decay using exponential decay curves with published hardwood and softwood specific decay constants (Russell et al. 2014). Downed wood biomass was comprised of all biomass lost to mortality, disturbance, harvest, and deforestation, from partial to full cohorts (e.g., individual trees or branches to full species-age cohorts), that remained on the landscape to decay in the simulations.

Biomass removal from harvest was modeled using the HWP-C vR harvested wood product model. The HWP-C vR model tracks harvested wood from milled roundwood to final products and discard fates and has been used for California, Oregon, and Washington's wood products carbon inventories (Figure 7; Groom and Tase 2022; Lucey et al 2024). For this study, we parameterized the model for southern New England using the most recently available local, regional, and national published accounts of different primary product ratios, end use ratios, end use half-lives, and discard ratios (specified in bullets below). This model is similar to the approach used in the original Land Sector Report of the MA 2050 Decarbonization Roadmap and includes many similar primary product and end use ratios; however, this new approach better estimates processes of recovery (e.g., recycling) and landfill carbon, as well as has more updated and refined end use categories.

To simulate current trends in wood utilization within each scenario, we used the aboveground harvest volumes removed by management area from each of the scenario simulations by species and age class cohort (what is available from LANDIS). To match these LANDIS outputs with the HWP model and TPO derived ratios, we needed to translate LANDIS age cohorts into size classes prior to analyses. As a rough division between poletimber and sawtimber size classes, age-class cohorts between the ages of 20 and 70 years were considered poletimber, and age-classes greater than 70 years were considered sawtimber (though in a real harvest and sale many other factors, including grade, influence if a specific tree is in fact growing stock and usable as sawtimber or poletimber). Any cohorts younger than 20 years were considered non-growing stock, alongside any cohorts removed from a non-commercial harvest (any age-class). Additionally, for the high-disturbance scenarios with simulated hurricanes, a proportion of the hurricane downed wood was added to the harvest volumes to simulate salvage harvests (26% of sawtimber, 10% of poletimber, and 0% of non-growing stock).

We then used the most recent southern New England Timber Products Output reports available to calculate the proportions of the harvested volume that is left on site as logging residue by species and size class (Forest Service 2018). The proportions of the removed wood that was left on the landscape as logging residue are subject to hardwood and softwood specific decay rates (Russel et al. 2014), using the same methods as for other downed wood left though other processes (see above). The volume of harvested wood not left on site was then passed to the HWP model to be simulated as roundwood sent to the mill to be processed.

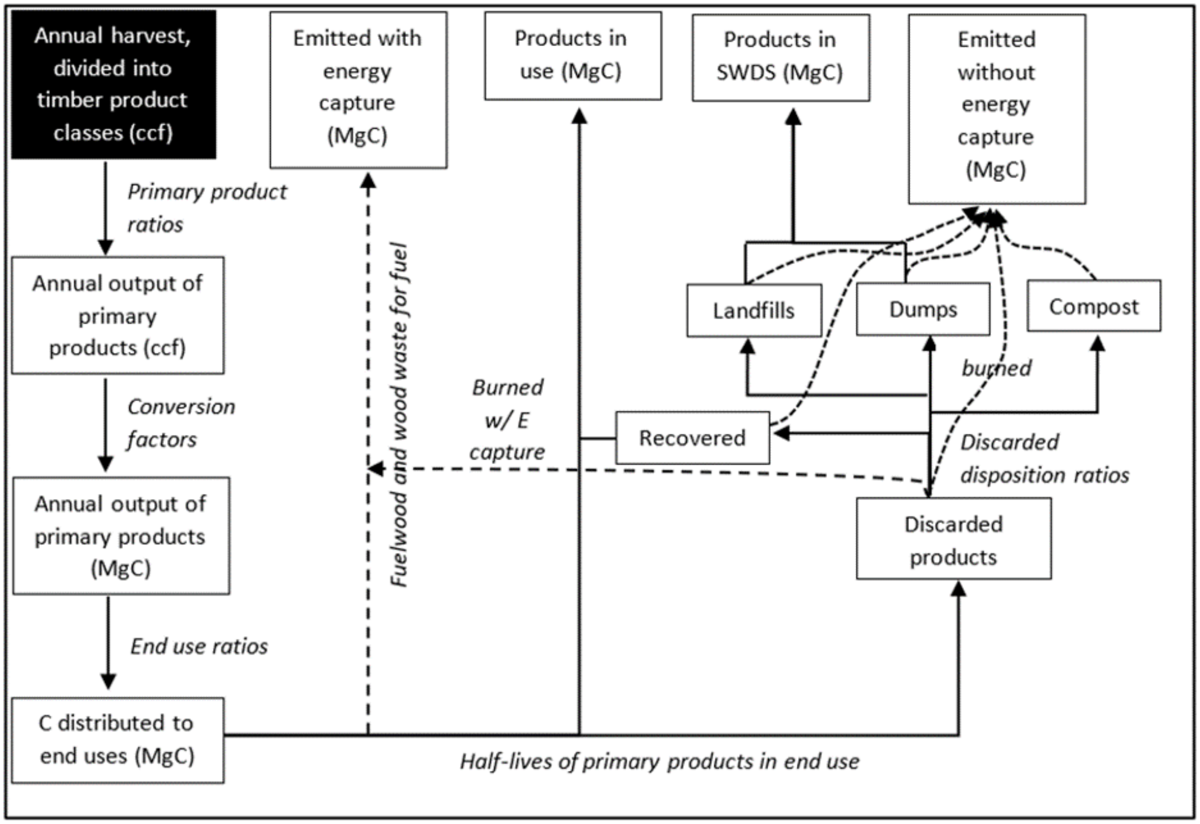

Figure 7. *Based on Stockmann et al. 2012, the general model used in the USFS harvested wood product carbon accounting model (Figure 2.1 in Groom and Tase 2022). Boxes on the left represent different stages of distributing the input harvest volume (black box where ccf = centum cubic feet or 100 cubic feet) into initial end uses in the first year (lower left box where MgC = megagrams of carbon). From here the model moves the carbon in these end uses into end carbon pools (all boxes to the right) for each year left in the simulation. For example, in year one, the carbon in a particular end use may be "in use", but by year five, most of the carbon is discarded based on the half-life of that end use). Solid lines represent processes where all carbon moves from one stage to the next and is stored in that pool. Dashed lines represent a process that results in an emission that could offset other energy production (e.g., burning of fuelwood), and a dotted line represents a process that results in emissions without energy capture (e.g., emissions from decaying wood products in solid waste disposal sites, (SWDS)).*

Based on data availability, TPO was used to estimate timber product ratios, Northeastern regional estimates of primary product ratios, and national level data on end use ratios were used to estimate end use ratios and disposal and decomposition rates for the harvested wood. The process for sourcing these ratios and rates is described in detail below:

- ***Timber product ratios*** – These values represent the proportion of total roundwood taken off the land during a harvest that goes into each of the 40 different potential timber product categories (e.g. hardwood roundwood, hardwood pulpwood; see Appendix V). These proportions are based on TPO estimates of volume in each of the roundwood categories from harvests in southeastern New England (Massachusetts, Connecticut, Rhode Island, and southern VT and NH). The ratios are calculated by species groups and size class. To more accurately capture trends in species volumes into different roundwood categories, species with relatively low volume represented in the TPO estimates were first combined into “Other hardwood” or “Other softwood” (depending on the species) but left the species with over 100 M cu. Ft. of harvested volume as individual species (a marked improvement on our previous methods that nearly immediately combined species into either hardwood or softwood). We then determined what proportion of the removed volume ended up as a roundwood product or as logging residue by species and size class. From these estimates, we also determined the proportion of wood that is milled that ends up as mill residue and either used as other products (e.g., animal bedding, mulch), burned on site, or left to decay. Mill residues were also simulated using the HWP model (e.g., a proportion of the harvested volume that ended up as mill residue was turned into mulch and emitted through decay).

- ***Primary product ratios*** – These values represent the proportion of the carbon that goes into each of the 64 possible primary products for each timber product category (e.g., softwood sawtimber may have several possible primary products, such as lumber or plywood). These ratios are from New England regional estimates of primary product production that have been updated from Smith et al. 2006 and Stockmann et al 2012 using 2018 TPO estimates of primary product production.
- ***End use ratios*** – These values (like the primary product ratios) represent the proportion of carbon that goes into each of the 224 possible end use categories from each primary product. These are from national estimates of end use production (McKeever 2009; McKeever and Howard 2011), since much of the wood turned into primary products does not remain in regional markets (e.g., lumber from our region may be used in housing starts in the south).
- ***Half-lives of primary products in end use*** – These values represent a measure of how long wood stays in each end use on average (the half-life) before being discarded. Standard national values from the HWP-C vR were retained for these half-lives (Groom and Tase 2022).
- ***Discard deposition ratios*** – These values represent the proportion of each discard type (i.e., paper, wood, lumber, plywood) that ends up in each discard fate (e.g., recycled, landfilled). Standard national values from the HWP-C vR were retained for these half-lives (Groom and Tase 2022).
- ***Half-lives of discarded products*** – These values represent a measure for how much of a discarded product is recovered (e.g., recycled) each year, how much of what is left is subject to decay, and how quickly the proportion that is subject to decay will decay in a dump or landfill. In an anaerobic environment like a landfill (low or no oxygen available to aid decomposition), not all of the carbon from discarded wood products will decay, so some of the carbon will remain fixed or stored in the solid waste disposal site (SWDS). Standard national values from the HWP-C vR were retained for these half-lives (Groom and Tase 2022). Emissions from SWDS are reported in CO2eq, but the model currently does not differentiate between methane and CO2 (although an update is underway).

Improved Wood Utilization

We also simulated a variant of the HWP model where we assumed an improved utilization of wood in which we assumed changes in logging and milling efficiency, additional markets for long-term wood products, and increased post-disturbance salvage logging. This scenario variant was designed with input from regional forestry experts and sought to explore the upper limits of how we may be able to improve wood utilization. The simulated logging and milling efficiency improvements seek to emulate improvements in logging and mill equipment and methods to reduce logging and mill residues. Logging residues are usually left on site (and subject to decay), while mill residues can be turned into other products, but are generally short-term wood products. In our improved wood utilization variant, we decreased the percentage of harvested biomass that becomes logging residues by 5% for the poletimber and sawtimber size classes, and 10% for non-growing stock. The additional 5% reduction of logging residues for non-growing stock wood represents better wood markets for lower quality wood (e.g., wood fiber insulation).

We also decreased mill coarse woody residues by 5% for all species and size classes and reduced other mill residues by 1%. This decrease in mill residues simulates smaller kerf widths (better milling equipment) which have been shown to improve overall efficiencies 2-3% in previous studies (Mitchell et al., 2005). Finally, we also increased the average proportion of wood going into longer-term products (end-use half-life of >65 years) from approximately ~44% to ~55% to simulate a change in markets, new products (e.g., cross-laminated timber (CLT)), forest aging, and better silvicultural strategies that result in higher grade logs.
Alongside these general changes, we also made two additional wood utilization improvements based on specific disturbances in our scenarios. In an effort to pair our timber use with species that may provide the greatest carbon gains with its use, we simulated that ~60% of all removed sawtimber hemlock biomass is turned into new mass timber products (e.g., CLT, glulam –glued laminated timber) with the same in-use half-life as other wood building materials (100 years), since in our recent trends in wood utilization most of the harvested hemlock ended up in shorter-term products (e.g., mulch). We also increased post-hurricane salvage logging from around 25% to around 74% (75% of sawtimber, 20% of poletimber, and 0% of non-growing stock) in this improved wood utilization scenario, assuming we greatly increase our capacity for rapid salvage logging.

3.7 Simulating Land Cover Change

We simulated land-cover change to project a continuation of recent trends (see Table 5) and to accommodate scenarios including new building development, new greenfield solar development, and new forest cover from reforestation and tree planting. Land cover change was simulated using the Dinamica EGO 7.4.0 cellular automata model (Soares-Filho, Coutinho Cerqueira, and Lopes Pennachin 2002). Dinamica is spatially explicit and incorporates spatial feedbacks and stochastic processes. The model uses the Weights-of-Evidence (WoE) statistical method to calculate transition probabilities for each pixel in a raster land cover map (Goodacre et al. 1993). We used LCMAP year 2020 to represent the initial land cover conditions and LCMAP landcover change during the historical reference period (2000 - 2020) to calculate the WoE transition probabilities for recent trends-based land cover change scenarios. When calculating the transition rates for the reference period (Table 5), we stipulated that any changes mapped between 2000 and 2020 needed to be persistent into 2021 to be counted as permanent change. This helps avoid misclassifying ephemeral changes such as timber harvest and shoreline water level fluctuations as permanent land cover change.

Estimates of terrestrial carbon within forest cover were based on LANDIS/PnET and refer to live and dead tree carbon, and do not include soil carbon. For all other land cover classes, a carbon bookkeeping approach was used following Tang et al. (2020), with carbon density coefficients derived from a literature review and detailed in Table 6.

Table 5. Areas and rates of land cover transition during the 2000-2020 reference period, used in recent trends-based land cover change scenarios for 2020-2050.

Original land cover class, 2000	New land cover class, 2020	Change area		Annual rate of change	
		hectares	acres	hectares/year	acres/year
Barren	Developed	4,060	10,032	203	502
Barren	Greenfield Solar	652	1,611	33	81
Barren	Tree Cover	350	865	18	43
Cropland	Developed	5,869	14,503	293	725
Cropland	Greenfield Solar	2,556	6,316	128	316
Cropland	Tree Cover	1,436	3,548	72	177
Developed	Tree Cover	4,795	11,849	240	592
Grass/Shrub	Developed	3,116	7,700	156	385
Grass/Shrub	Greenfield Solar	409	1,011	20	51
Tree Cover	Barren	7,729	19,099	386	955
Tree Cover	Cropland	8,925	22,054	446	1103
Tree Cover	Developed	28,187	69,651	1,409	3483
Tree Cover	Greenfield Solar	5,930	14,653	297	733
Wetland*	Greenfield Solar	78	193	4	10

* Wetland conversions depicted here are based on LCMAP land cover data, however, MassDEP-mapped wetlands were excluded from solar development.

Table 6. Biomass carbon density estimate for each modeled land cover class. Includes live and dead biomass pools, but not soil carbon.

Land Cover Class	Source	$MTCO_2e$/ha	$MTCO_2e$/acre
Highest-Density Development	Meta-analysis in Appendix IV: Terrestrial Carbon in the Developed Environment	0	0
High Density Development		72.3	178.66
Medium Density Development		136.67	337.72
Low Density Development		178.47	441.01
Tree Cover	LANDIS	2020: 0.00 - 668.30 2050: 0.00 - 680.05 2100: 0.00 - 814.01	2020: 0.00 - 1651.40 2050: 0.00 - 1680.44 2100: 0.00 - 2011.46
Cropland	Land Sector Report (tables 5 and A3)	23.78	58.76
Grass/shrub		23.78	58.76
Water		0	0
Wetland (non-forested)		6.97	17.22
Barren		0	0
Solar	Assumed	0	0

Building Development

For all scenarios, building development locations and patch sizes are estimated based on analysis of observed greenfield building development during the 2000-2020 reference period per USGS LCMAP and associated spatial predictors. The methodology follows Thompson et al. (2017, 2020). Spatial predictors for building development include distance to population centers, population density, distance to roads, distance to development, slope, landowner type, wetlands, and flood zones. The area subject to building development varies among scenarios and is described below.

Alternative building development scenarios are intended to estimate the land carbon effects of greenfield development of buildings and associated infrastructure. These scenarios do not assume a particular amount of total development, infill development within existing settlements, or population growth; rather, they only reflect potential rates and patterns of greenfield development (i.e. expansion of development into undeveloped areas) that could be driven by variety of factors including land-use policy, development economics, population dynamics, and cultural preferences. Building development in the scenarios are shown in Table 7. The rate multipliers used in the Sprawl and Compact scenarios come from the New England Landscape Futures (NELF) 'Yankee Cosmopolitan' and 'Connected Communities' scenarios respectively (Lambert et al. 2018; Graham MacLean et al. 2021; Thompson et al. 2020).

Table 7. *Scenario parameters used to simulate new building development*

Scenario	**Greenfield development, 2020-2050** (area, growth from 2020 developed area)	**Development rate multiple** (relative to reference scenario)	**Notes**
Recent trends building development	41.2K ha (101.8K acres), +7.9%	1.00	Based on 2000-2020 reference period; excludes solar development and barren land.
Compact building development*	13.7K ha (33.9K acres), +2.6%	0.33 (1/3 *Recent Trends* development rate)	Informed by NELF "Connected Communities" scenario
Sprawl building development*	82.5K ha (203.9K acres), +15.9%	2.00 (2x *Recent Trends* development rate)	Informed by NELF "Yankee Cosmopolitan" scenario
Counterfactual (no greenfield development)	0 ha (0 acres), +0%	0.00	Baseline "control" scenario for comparison; could also be considered a hypothetical all infill development scenario

* Scenarios were used to simulate greenfield building development in the Integrated Scenarios, while all four were evaluated as Building Development Focus Scenarios.

Solar Development

Estimates of future greenfield solar quantity, siting location, and patch sizes were based on observations of greenfield solar development during the 2010-2020 reference period (Manion et al. 2023) and their relationship to a suite of spatial predictors. Spatial predictors include physical site characteristics such as slope, aspect, and land cover; socio-economic metrics such as land price, population density, and distance to development; and infrastructure variables such as distance to substations, roads, and existing solar installations. We used the Weights of Evidence statistical method to generate patterns of future solar development in Dinamica EGO. The contribution of each spatial predictor variable to the final probability-of-solar map is detailed in Figure A3 of Appendix V. The rate of solar development was set to achieve the anticipated need for 27 GW of capacity by 2050, per analysis behind the Massachusetts 2050 Clean Energy and Climate Plan (EEA 2022), though 27 GW may be an underestimate or overestimate, depending on the availability of other sources of clean energy generation and level of demand management that can be achieved. The area needed to reach 27 GW_{ac} was estimated exploring the impact of several assumptions about future alternative energy build-out.

- First, we examined total land requirements using two different estimates of land use intensity, or land area required per unit of solar power production capacity (Table 8 - Land Use Intensity): (1) 1.46 ha/MW_{ac} which is consistent with the Massachusetts Department of Energy Resources (DOER) *Technical Potential of Solar Study* (DOER 2023) and is originally derived from Bolinger and Bolinger (2022). (2) 2.75 ha/$MW_{ac,}$ which is the current observed land use intensity of greenfield solar facilities since 2005. To calculate the current observed land use intensity of solar energy production we use the average of two different methodologies: a site-based approach and an aggregate-based approach. For the site-based approach, two researchers used high resolution satellite imagery from Google Earth to digitize the disturbed area surrounding a sample of 31 greenfield solar sites with known production capacities. This included the panels, area between panels, access roads, and buffers surrounding the site to eliminate shading or to install fencing. Due to expected differences in digitizing technique, the first experiment resulted in 3.28 ha/MW and the second resulted in 2.80 ha/MW for an average of 3.04 ha/MW. For the aggregate-based approach, we combined Harvard Forest's dataset of greenfield solar sites which is an amalgamation of mapping efforts conducted by DOER,[7] Clark University (Tao et al. 2023), and Harvard Forest (Manion et al. 2023) with the total installed capacity reported in the Technical Potential of Solar report (DOER 2023). We examined sites that were installed from 2005 onwards and were classified as "Ground-mounted (large ≥ 1MW)". Additionally, we included 50% of those classified as "Other". This resulted in 3,377 ha of disturbed area producing 1.38 GWAC for a land use intensity of 2.44 ha/MW. As a final step, we averaged our result from the site-based approach (3.04 ha/MW) with our aggregate approach (2.44 ha/MW) to get 2.75 ha/MW which we used for our current estimate of land use intensity. To account for potential gains in efficiency over time, we also included an "improving energy production" scenario that decreases the ha/MW_{ac} from 2.75 to 1.46 linearly from 2020-2050.
- Second, we examine different assumptions about the proportion of future solar development needed to achieve 27 GW of production that would be sited on undeveloped land ("greenfield") as opposed to on rooftops or otherwise integrated into the already developed land. We simulated different proportions of production from greenfield solar development (Table 8 – Greenfield Proportion & Figure 8), including

[7] https://www.mass.gov/info-details/annual-compliance-reports-and-other-publications

high (67%), moderate (50%), low (33%), as well as a counterfactual no development (0% i.e. all new solar on developed land) that was only used as a baseline for comparison.

- Finally, we included two different siting patterns -- i.e, where greenfield solar is permitted on the landscape (Table 8 – Siting). The first scenario follows recent trends patterns observed between 2010 and 2020, whereas the second restricts solar siting on sites deemed as conservation priorities in the recent *Growing Solar Protecting Nature* report (Manion et al 2023; Table 9) and under consideration by EEA and DOER.

Table 8. *Parameters for greenfield solar development scenarios.*

Scenario	**Greenfield proportion** % of all capacity in 2050†	**Land Use Intensity** ha/MW_{AC} (acres/MW_{AC})	**Area of greenfield solar development, 2020-2050** hectares (acres)	**Siting Criteria** (see Table 9)
High footprint & recent trends siting*	High (67%)	Current: 2.75 (6.80)	40.6K (100.3K)	Recent trends-based
Low footprint recent trends siting	Low (33%)	Low 1.46 (3.60)	14.6K (36.1K)	Recent trends-based
Low footprint & conservation siting*	Low (33%)	Low 1.46 (3.60)	14.6K (36.1K)	Conservation-based
Moderate footprint & recent trends siting	Moderate (50%)	Improving: 2.75 (6.80) in 2020 to 1.46 (3.60) by 2050	25.1K (62.1K)	Recent trends-based
Moderate footprint & conservation siting	Moderate (50%)	Improving 2.75 (6.80) in 2020 to 1.46 (3.60) by 2050	25.1K (62.1K)	Conservation-based
No greenfield development counterfactual (used as baseline for comparison)	0%	-	0	-

* These scenarios were used to simulate high and low levels of greenfield solar development in the Integrated Scenarios, while all six scenarios were evaluated as Solar Development Focus Scenarios.

† Remainder of new solar assumed to be in developed areas.

Table 9. *Greenfield solar siting exclusion criteria.*

Exclusion Criteria	Recent Trends based siting	Conservation based siting
Permanently protected land (MassGIS Protected & Recreational Open Space)	X	X
Wetlands (MassDEP)	X	X
Open Water (USGS LCMAP landcover)	X	X
Developed land (USGS LCMAP landcover), plus:	X	X
Buildings (50ft buffer)	X	X
Airport parcels	X	X
Roads (50ft buffer)	X	X
Residential lots <= 1ac with buildings	X	X
Active rail lines	X	X
Parking lots	X	X
Cemeteries	X	X
Slope > 8 degrees	X	X
Highest 75% of carbon stocks (this study)		X
BioMap Core and Critical Natural Landscapes		X
Wetlands (100ft buffer)		X
Climate-resilient sites (> avg. landscape diversity & connectedness from TNC Resilient Lands map)		X
Prime farmland soil (NRCS)		X

Note: Conservation-based siting follows the “Protecting Nature - Mid scenario” within the *Growing Solar Protecting Nature* report (Manion et al 2023), and new siting criteria either adopted or under consideration by DOER and EEA for Massachusetts’ SMART solar incentive program.

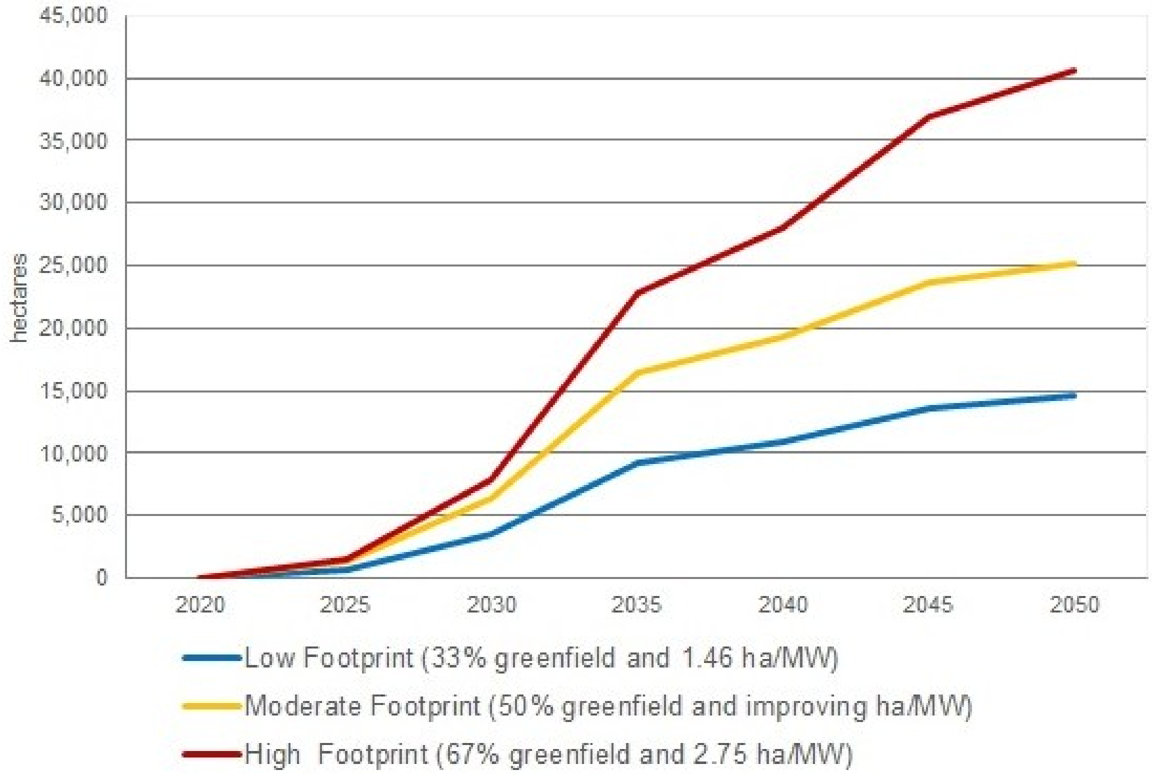

Figure 8. *Area of greenfield solar development by 5-year timestep in the Solar Focus Scenarios.*

Reforestation and Tree-Planting

Alternative reforestation and tree-planting scenarios were intended to estimate the carbon sequestration potential of expanding forest and tree canopy cover on suitable non-forest land throughout Massachusetts. The focus was on undeveloped areas, where restoration of large areas of open space to forest ecosystems (i.e. *reforestation*) is plausible, and where potential for carbon gains and forest expansion is greatest. The analysis also includes more urbanized areas, where the planting of individual tree saplings (i.e. *tree-planting*) in developed open spaces (e.g. parks) or within the built environment (e.g. street trees) is more likely.

Land with reforestation potential was identified within rural (i.e. non-urbanized) areas of the state, while land with tree-planting potential was identified within urbanized areas, based on 2020 U.S. Census urban area designations (Census Bureau 2023). Within each of these designations, land suitable for reforestation or tree planting is identified based on criteria that include land cover, proximity to water bodies (riparian areas), suitability for agricultural use, and features that may constrain planting in developed areas (Table 10). These areas of reforestation and tree-planting opportunity are informed by and consistent with those identified in Massachusetts' *Healthy Soils Action Plan* (EEA 2023a) and *Resilient Land Initiative* (EEA 2023b), as well as in the scientific literature (Cook-Patton et al. 2020).

Table 10. *Reforestation and tree planting opportunities identified for Massachusetts.*

Opportunity Class	Eligible Land Categories	Tree Planting Density trees/ha (trees/acre)	Specific Criteria	Available Area ha (acres)
Rural reforestation Land outside 2020 Census urban areas	Rural riparian buffers	NA*	Grass/Shrub or Cropland (LCMAP landcover) within 30m (100ft) of inland water bodies (MassDEP Hydrography)	6.6K (16.4K)
	Rural open space	NA*	Grass/Shrub or Cropland (LCMAP landcover) outside 30m riparian buffer and not on prime farmland soils (NRCS)	72.3K (178.7K)
			Total reforestation area:	79.0K (195.1K)
Urban tree-planting Land within 2020 Census urban areas	Urban riparian buffers	248 (100)	Cultivated Crops, Pasture/Hay, Grassland/Herbaceous, Developed Open Space (MassGIS 1m landcover) within 30m (100ft) of inland water bodies (MassDEP Hydrography)	5.3K (13.1K)
	Urban open space	124 (50)	Developed Open Space (MassGIS 1m landcover) outside 30m riparian buffer	121.2K (299.5K)
	Parking lots	62 (25)	Parking lots, as identified in Healthy Soils Action Plan parking lot analysis	28.2K (69.6K)
	Street trees	40 (16)	Local & major roads with shoulder, sidewalk, and/or median ≥ 6ft; no existing tree canopy (MassGIS/DOT Roads)	10.2K (25.1K)
			Total tree-planting area:	164.9K (407.4K)

* Modeled as forest area, not as individual trees.

Carbon sequestration rates for reforestation areas were estimated using the same LANDIS/PnET growth model that was used to simulate existing forest ecosystems in this study. We estimated species-by-ecoregion-specific growth rates and used a bookkeeping approach to estimate state-level carbon accumulation for reforestation. To select species for reforestation, we used forested USDA Forest Inventory and Analysis (FIA) Massachusetts' plot data to estimate tree species composition and density for each unique LANDIS ecoregion (see section 3.3), and filtered plots to make sure the dominant species were well-suited to the current and future growing conditions, and then selected the five most dominant species (by density) in each ecoregion. For example, the long-term viability of both eastern hemlock and ash species are uncertain due to the prevalence of invasive insects, therefore we did not include them as dominant species in our reforestation scenarios. There were a few cases where there were fewer than five suitable species present in the FIA plots in a Landis ecoregion (see section 3.3), because either the FIA data have fewer than five species or the plots contain unsuitable species. To calculate the growth and mortality rates of the dominant species in each ecoregion, we represented each ecoregion as a single cell in LANDIS/PnET. The ecoregion-specific net sequestration rate was then imputed using a bookkeeping approach to all reforestation areas within that ecoregion. Mean annual sequestration varied by ecoregion, planting year, and time since planting, where it was highest after approximately 30 years growth (Table 11).

Table 11. *Summary statistics of carbon removal rates and live carbon densities from reforestation across ecoregions and over time. Carbon removed from the atmosphere and stored in tree biomass is expressed as a negative removal rate, while positive rates indicate net emissions. Live carbon densities are expressed as positive values.*

Cohort age	**Annual carbon removal rate ($MTCO_2e$/ha)**			**Live carbon density ($MTCO_2e$/ha)**
	maximum	minimum	mean (std. dev.)	mean (std. dev.)
5	-6.28	-1.12	-3.74 (1.20)	37.05 (5.16)
10	-9.7	-1.31	-5.34 (1.95)	57.82 (12.79)
15	-16.74	-1.74	-8.72 (3.41)	91.21 (25.32)
20	-25.92	-2.94	-11.97 (5.11)	140.40 (47.12)
25	-21.97	-3.21	-11.87 (5.12)	200.90 (69.44)
30	-34.54	-5.60	-15.8 (4.64)	272.49 (86.56)
35	-21.33	14.43	-12.6 (4.33)	336.21 (92.56)
40	-18.76	65.23	-9.12 (12.29)	382.81 (89.04)
45	-24.68	58.05	-8.52 (11.53)	412.16 (90.51)
50	-22.57	45.32	-6.52 (10.23)	443.94 (94.52)
55	-22.04	137.10	-1.76 (27.5)	469.68 (97.75)
60	-17.94	136.46	-3.07 (21.6)	497.59 (105.71)
65	-19.36	43.12	-4.29 (8.10)	520.90 (112.47)
70	-17.87	100.10	-6.12 (13.05)	551.55 (114.99)
75	-18.46	12.00	-6.35 (5.73)	551.84 (129.28)
80	-14.91	435.28	2.47 (52.53)	545.56 (149.87)

For tree-planting in urban areas, we modeled the growth of saplings planted in urbanized areas, including in developed open space areas (parks and riparian buffers) and within the built environment (street rights-of-way and parking lots; Table 10). Newly planted trees were allocated to each eligible urban land category in proportion to available land area at category-specific densities (40-248 trees/ha) based on DCR staff recommendations (Table 10). Net carbon sequestration rates were derived from a study of urban tree ecosystem services in two Massachusetts' cities (Moody et al. 2021) based on an individual urban tree model (i-Tree; Nowak 2020). All trees were estimated to sequester 1.7 $kgCO_2e$/tree/year over the first three years post-planting, after which net sequestration rates increased by either 0.1 $kgCO_2e$/tree/year, accounting for typical mortality rates, or by 0.2 $kgCO_2e$/tree/year, for improved stewardship scenarios with lower mortality (halfway between sequestration rates with typical mortality and no mortality).

Reforestation and tree-planting scenarios follow those outlined in the *Healthy Soils Action Plan* (EEA 2023a), whereby new tree cover is realized on 10%, 25%, and 50% of potential available land between 2020 and 2050, corresponding to “modest”, “ambitious”, and “maximum” efforts (Table 12). This new tree cover is in addition to baseline rates of reforestation and tree planting. The baseline tree planting rate follows data reported by Massachusetts’ Greening Gateway Cities program (6,156 trees/year since 2017, excluding 2020 as a pandemic-related outlier) (Moody et al. 2021). The baseline rate of reforestation (i.e. passive reforestation) is estimated from the 2000-2020 LCMAP reference period (329 ha/yr, 813 ac/yr; Table 5). In the Integrated Scenarios, we used the ambitious level of reforestation and tree planting (in addition to passive reforestation rates) for the coordinated land cover change regimes and the baseline reforestation and tree-planting rates for the uncoordinated land cover change regime.

Table 12. *Parameters for reforestation and tree-planting scenarios.*

Scenario	**Realized tree cover potential by 2050** % of suitable land	**Actively Reforested Area** ha (acres)	**Additional Tree-Planting Area** ha (acres)	**Total Area** ha (acres)
Maximum feasible	50%	39.5K (97.6K)	82.4K (203.7K)	121.9K (301.2K)
Ambitious*	25%	19.8K (48.8K)	41.2K (101.8K)	61.0K (150.6K)
Modest	10%	7.9K (19.5K)	16.5K (40.7K)	24.4K (60.2K)
Baseline*	0%	0	0	0

* These scenarios were used to simulate high and low levels of reforestation and tree-planting in the Integrated Scenarios, while all four scenarios were evaluated as Reforestation/Tree-Planting Focus Scenarios.

Note: These numbers reflect reforestation and tree-planting that is additional to baseline rates, which are assumed in all scenarios and includes reforestation during the 2000-2020 reference period (329 ha/yr, 813 ac/yr) and current tree-planting rates (6,156 trees/year).

3.8 Integrated Scenarios

The Integrated scenarios establish a plausible range of possible future forest carbon sequestration and storage in Massachusetts, accounting for the upper and lower bounds of assessed forest management regimes, ecological disturbances, and drivers of land cover change. The Integrated Scenario framework includes eight scenarios encompassing four forest management regimes (Table 1 columns) in combination with two land disturbance regimes (Table 1 rows), where the land disturbance regimes reflect different levels of ecological disturbances and land cover change. The scenario matrix was developed to allow decision-makers to better understand the potential outcomes of forest management under low disturbance (natural and anthropogenic; bottom row) and high disturbance (top row) natural and anthropogenic disturbance regimes. The details of the scenario parameters are documented in

Tables 14A-C below. All components of the Integrated Scenarios were modeled for the period 2020 to 2050, while a separate set of simulations modeled the scenarios without the land cover change components for the period 2020 to 2100. This two-period approach was used due to particularly high levels of uncertainty around post-2050 land cover change dynamics.

The four different forest management regimes vary in terms of the harvest practices (including total volume, area, and species harvested), reserve areas, and wood utilization (Table 14A). The different levels of ecological disturbance reflect futures with either minimal high-impact disturbances or with climate-intensified disturbances, including high-impact hurricanes. The land-cover change alternatives represent futures of either uncoordinated land-cover change, mostly following recent trends but including a large build-out of solar facilities to meet the Commonwealth's clean energy goals or coordinated land-cover change with compact building development patterns, more efficient solar siting, and ambitious reforestation and tree-planting efforts.

Table 13. *Summary of key drivers for the Integrated Scenarios (see Table 1). A. Forest management regimes. B. Levels of ecological disturbance. C. Land cover change alternatives.*

A. Forest Management Regime	Forest Harvesting	Forest Reserves	Wood Utilization
Recent Trends	Current forestry practices and harvesting levels	Current forest reserves	a. Recent trends b. Improved
Reserves Emphasis	Climate-oriented forestry, current harvest levels	Expand reserves to 1/3 of forest land	a. Recent trends b. Improved
Local Wood Emphasis	Climate-oriented forestry, increased harvest levels to meet 20% of MA wood consumption	Current forest reserves	a. Recent trends b. Improved
Combined Emphasis	Climate-oriented forestry, increased harvest levels to meet 15% of MA wood consumption	Expand reserves to 20% of forest land	a. Recent trends b. Improved

B. Ecological Disturbance Level	Gap-Scale Forest Disturbances	Insect Pests	Hurricanes
High Ecological Disturbances: Combination of disturbances representing a high-impact future	Climate change-intensified	Ongoing (hemlock wooly adelgid, emerald ash borer)	Climate change-intensified
Low Ecological Disturbances: Combination of ecological disturbance representing a low-impact future	Recent trends	Ongoing (hemlock wooly adelgid, emerald ash borer)	None

Table 13, continued. *Summary of key drivers for the Integrated Scenarios.*

C. Land Cover Change Alternatives	Building Development	Solar Development	Reforestation & Tree-Planting
Uncoordinated Land Cover Change: A future with high levels of net forest loss and land conversion	Sprawl development: -2X recent rate of greenfield development (2000-2020 reference period) -18% growth in developed area from 2020-2050 -82.4K ha (203.9K acres)	High footprint & impact solar development: - Growth to reach 27 GW projected need - High proportion of greenfield PV (2/3) by 2050 - High land use intensity (2.75 ha/MW_{AC}; 6.8 acres/MW_{AC}) -40.6K ha (100.3K acres) - Recent trends-based siting	Baseline reforestation and tree-planting (based on recent trends)
Coordinated Land Cover Change: A future with low net deforestation future	Compact development: -1/3 recent rate of greenfield development (2000-2020 reference period) - 2.6% growth in developed area from 2020-2050 -13.7K ha (33.9K acres)	Low footprint & impact solar development: - Growth to reach 27 GW projected need - Lower proportion of greenfield PV (1/3) by 2050 - Low land use intensity (1.46 ha/MW_{AC}; 3.6 acres/MW_{AC}) -14.6K ha (36.1K acres) - Conservation-restricted siting	Ambitious reforestation: Reforestation or tree-planting on 25% of available land

3.9 Assessing Forest Adaptive Capacity and Resilience to Climate Change

Massachusetts' forests are vulnerable to stressors exacerbated by climate change and have diminished adaptive capacity (Janowiak et al 2018). For example, altered natural disturbance regimes (e.g., fire, flooding) affect the ability of regeneration to establish; altered winter processes such as snowpack and freeze-thaw cycles affect browse susceptibility and the ability of harvest operations to scarify soils and prepare seedbeds; the presence of invasive plants can alter patterns and timing of regeneration establishment; changes in temperature and precipitation patterns can affect the survival of regeneration; high stand densities can promote conditions that make trees more susceptible to fungal infections and pathogens; and past land use practices and introduced forest pests have altered species composition (either increased richness through invaders in disturbance-prone communities where disturbance has been suppressed, or reduced through harvesting. Some management may be necessary to facilitate resistance, resilience, and adaptation to future conditions to avoid diminishment of ecosystem services, including carbon sequestration (e.g., Domke et al. 2023). Drawing from the literature for assessing, planning, and managing for forest resilience (e.g. Swanston et al. 2016, Ferrare, Sargis, and Janowiak 2019, Catanzaro, D'Amato, and Huff 2016.), key metrics associated with forest health and resilience used in this study include:

- Regeneration of species appropriate or critical to the forest community type (e.g., regeneration of oak and hickory species in oak-hickory communities; regeneration of spruce species and fir in spruce-fir communities, etc.),

- A level of species richness and diversity appropriate for the forest community type, measured within and across modeled age classes or groups of age classes,
- Proportion of biomass in species projected to be well-adapted to Massachusetts' expected future climate, and
- Site- and landscape-scale patterns of forest structural diversity and age class diversity.

Some indicators of forest health and resilience, such as stand density, are unable to be easily assess with the modeling approach used in this study. These metrics were determined after the COF/CSF prescriptions were designed, so the ability to tailor the prescriptions to address specific indicators was limited.

Forest Structure

Forest structure includes the vertical and horizontal arrangement of live, standing dead, and down dead vegetation, including trees, shrubs, and ground cover. Forest structure can be classified in a variety of ways, sometimes related to the proportions of trees of different sizes or related to both the sizes of trees and vertical and horizontal distribution of foliage and dead trees. The arrangement of forest structural conditions on the landscape has important implications for a variety of ecosystem services, including habitat and water quality. For example, different wildlife species depend on different amounts, patch sizes, and distributions of different structural stages for different parts of their life cycle.

To assess changes in forest structure in different modeled scenarios, it was necessary to translate model output into relevant metrics of forest structural conditions. Available model output includes biomass in each species-age cohort in each grid cell and time step. Forest structure, while related to tree age, is dependent on other factors without consistent relationships to age, such as tree size and the vertical and horizontal distribution of vegetation, which are not represented in the LANDIS/PnET model. Also confounding the approach was the fact that the process of assessing tree age occurred via a process of reverse-engineering age from tree height and site index for initial communities (described below), and within the model in a fashion consistent with time since establishment.

A variety of algorithms that classified the model output into different structural conditions were compared. The core approach was to calibrate and apply different models on the initial community dataset, for which both estimates of biomass and forest inventory data were available, at the level of individual raster cells. Expert staff and collaborators were consulted to provide feedback. Ultimately the selected approach used combinations of the tree size and horizontal and vertical arrangement of vegetation in the inventory data to predict stand structural stages. The RUSBoost algorithm (Matlab 2023) was used to construct a classification model to then predict structural stage from the amount and arrangement of biomass by age cohort. It provided reasonable results given the imbalance in actual initial landscape structural conditions. See Appendix VI for additional information.

A variety of metrics related to structural classes are important for habitat (e.g., patch size, core area, connectivity) and water quality (e.g., proportion of watershed in different structural classes) are important. In the context of this exercise, patch size was deemed a metric that could be calculated relatively easily and would be somewhat meaningfully linked to the quality of the initial input landscape (see the earlier comparative discussion of estimates of current forest structural conditions). Since management activities could not be located in the model to optimize connectivity, metrics related to connectivity were deemed less valuable for this exercise. For this component of the analysis, the two youngest structural conditions were grouped together, and the total area, and area in contiguous patches (rook's case), was calculated for each scenario and time step.

Forest Composition

The proportion of biomass in different species was also of interest. There area differing views over how to group species (e.g. whether to use the projected adaptability of species to Massachusetts' expected future climate, whether a species played a keystone role in ecosystems, etc.), and which age classes to use. While having biomass in species expected to fare better in the future is important, some better-adapted species are also ecological generalists, like red maple; and other species not expected to fare well like spruce and fir are still of critical importance in Massachusetts. Thus, judging success based solely on an increase of the proportion of biomass in species expected to fare well under a changing climate was deemed unproductive. Keystone species vary by region and forest type (e.g. oak species are central to oak-hickory forests but not as much to spruce-fir) so any assessment of keystone species would have to be community-specific. Finally, older, larger, and more-established trees have exponentially more biomass than younger tree, which are more vulnerable to the increasing stressors and disturbances expected under climate change, so partitioning biomass by age class was also expected to be important. Species were thus grouped by management priority, which included a combination of expected adaptability to future climate change and ecological role. Table A7 in Appendix VI shows the management priority ratings.

A series of case studies was developed to explore the effects of silviculture in specific natural communities commonly found in different regions of the Commonwealth. We developed definitions of natural communities that could be applied to the model output, attempting to match community definitions to the forest type variable value in FIA data based on tree species biomass dominance of the initial landscape plots. While not a perfect match, this approach provides some consistency with existing systems and empirical data. Areas that met these definitions after the model initialization period were identified. Areas that were treated after the model initialization period were separated from those that were never treated. Metrics relevant to the community were identified, including those related to species composition, species diversity, and age class diversity. Specifically, the proportion of the communities' biomass in keystone species—the species that defined the community and were central to its functioning and perpetuation—were important. Mean values for those metrics were calculated for harvest events and unharvested areas immediately before and after treatment, and 10, 30, 55, and 75 years after, tracking those same treated areas over time; and from the same time steps in untreated areas. After the treatment, both treated and untreated areas were subject to the same natural processes depending on where they were in the management priority filter described earlier, and treated areas may have been treated again at a later time step.

4. Results

4.1 Integrated Scenario Results

Land Carbon Results to 2050

All eight scenarios resulted in net removal of carbon from the atmosphere through 2050, with the cumulative net carbon flux ranging from -161.7 to -39.6 $MMTCO_2e$ (Figure 9), equivalent to an annual average of -1.3 to -5.4 $MMTCO_2$/yr. In 2050, under the high disturbance scenarios, live landscape carbon decreases (Figure 10), but when accounting for both live and dead carbon stocks, total carbon stocks increase under all scenarios. The scenario results are clustered into two groups: those with high levels of ecological disturbance and land cover change (the top four scenarios in Table 1) and those with low levels of ecological disturbance and land cover change (the bottom four scenarios in Table 1). Insomuch as these two groups represent high- and low-emissions futures from an exogenous disturbances perspective (i.e. those outside the forest management decision space), these results suggest that in a high-disturbance future, the impacts of forest management decision-making span 33 $MMTCO_2e$ (from –39.61 to –72.97 $MMTCO_2e$) over the 2020 to 2050 time period; in contrast, in a low-disturbance future, the impacts of forest management span 28 $MMTCO_2e$ (from –133.98 to 161.71 $MMTCO_2e$) (Table 15).

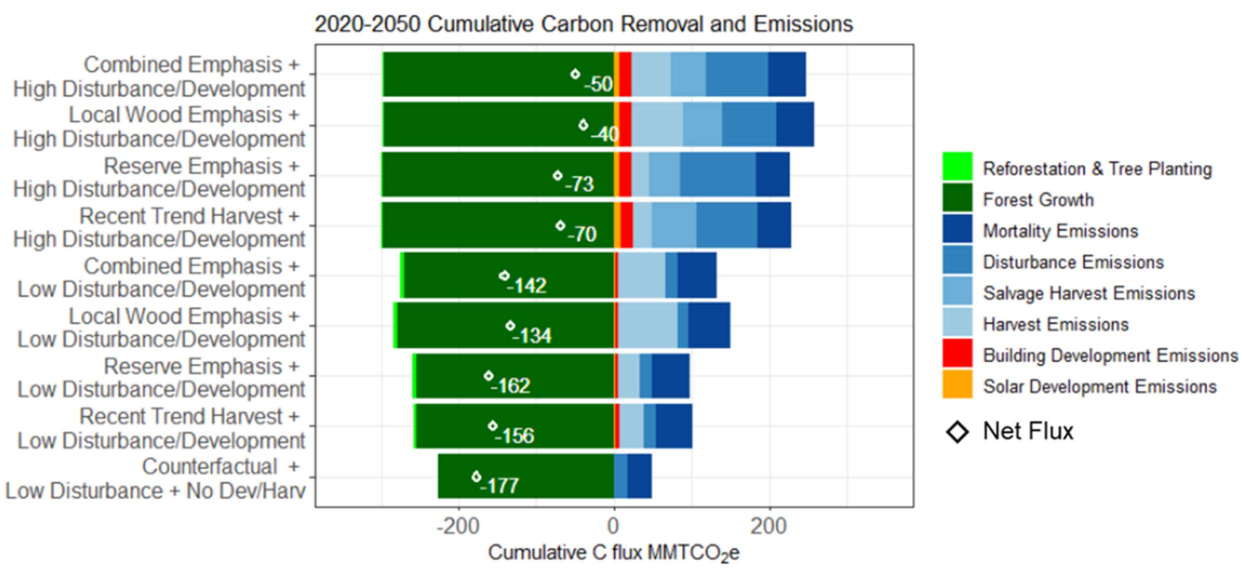

Figure 9. *Cumulative fluxes of carbon between 2020 and 2050 for each of the eight Integrated Scenarios and a counterfactual scenario (no development or harvesting). Green bars to the left represent cumulative removals (i.e. sequestration), bars to the right represent cumulative emissions, and white diamonds show the cumulative net flux to the atmosphere. Carbon transfers between all simulated pools are accounted for, including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills. The white diamonds represent the difference between cumulative removals and emissions–i.e, the total net flux to the atmosphere.*

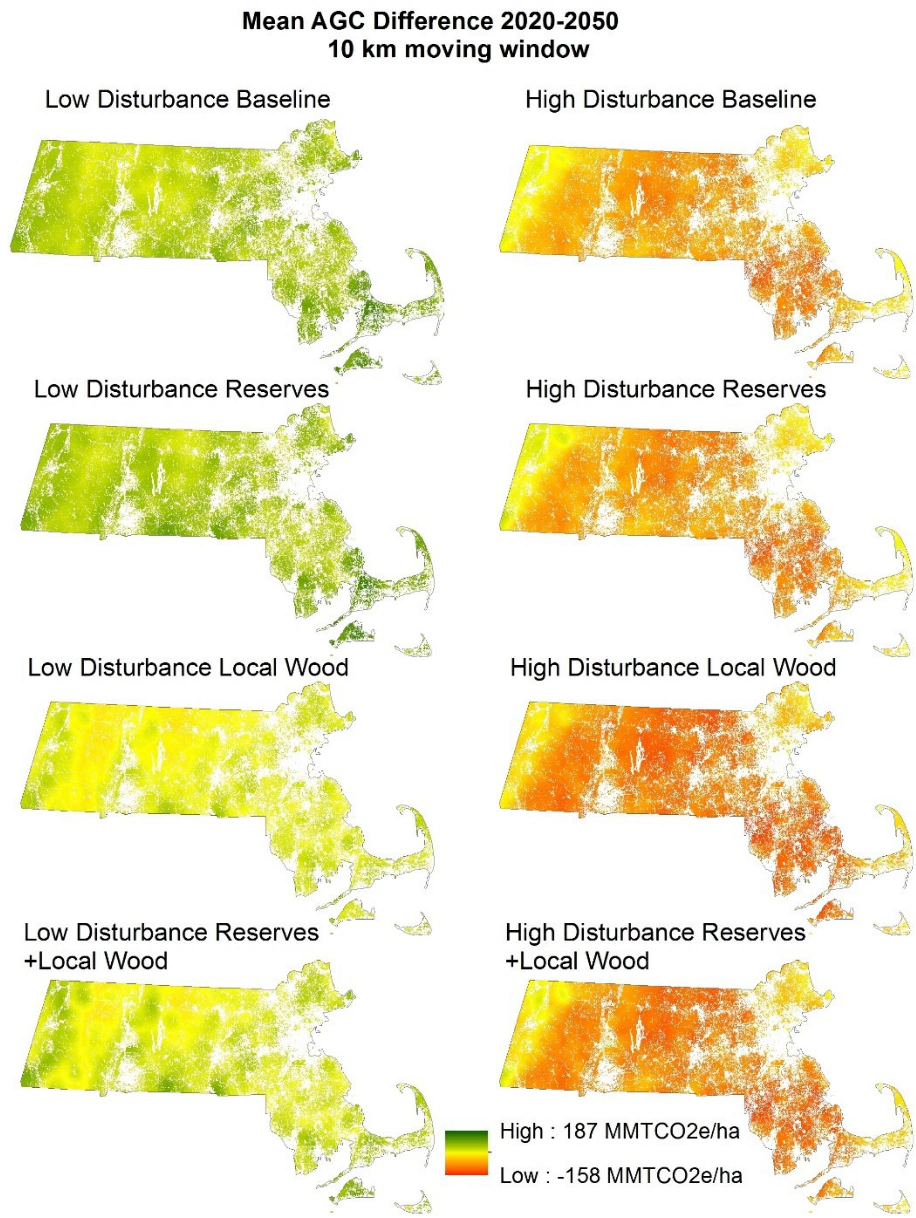

Figure 10. *Change in live carbon density (above- and below-ground biomass) 2020-2050 for the Integrated Scenarios. Areas in green have increases in live carbon while areas in red experienced losses. Maps show average live carbon density within a 10km moving window to highlight regional patterns.*

Among the Integrated Scenarios, the low-disturbance Reserve Emphasis Scenario resulted in the highest cumulative net sequestration by 2050 (-162 MMTCO$_2$e as compared to -156 MMTCO$_2$e for the comparable Recent Trends). This scenario had a similar level of forest growth as the low-disturbance Recent Trends (-254 and -253 MMTCO$_2$e, respectively) but had lower emissions (97 and 102 MMTCO$_2$e, respectively). In the Reserve Emphasis Scenario, approximately one-third of the state's forest land (399,138 ha or 986,291 acres) is off-limits to harvesting and development. However, the volume of harvesting and the area developed within the state was similar to Recent Trends. This was done to minimize the effects of leakage, wherein any decrease in harvesting or development would have moved out of state. The result is a large shift in the spatial distribution of land use, but minimal changes in the terrestrial carbon stocks of forests remaining forests when measured at the state-scale. Within the newly defined reserve areas for the Reserve Emphasis scenario, above ground live carbon accrued to an average of 374.3 $MTCO_2e$/ha, compared to 345.0 $MTCO_2e$/ha in those same areas in the Recent Trends scenario.

Table 15. *Summary of carbon fluxes ($MMTCO_2e$) for each of the Integrated Scenarios over the 2020-2050 modeled time period. Flux attribution (e.g. to forest harvest, building development etc.) reflects direct emissions only, not indirect effects (e.g. growth enhancement, reduced mortality, or foregone sequestration), which are accounted for in the Forest growth and Forest mortality rows. Forest management regimes are abbreviated as follows: RT = Recent Trends, Reserv. = Reserve Emphasis, LW = Local Wood Emphasis, Comb. = Combined Emphasis. Ecological disturbance and land cover change regimes are abbreviated as: Low Dist. = Low Disturbance/Development, and High Dist. = High Disturbance/Development.*

Scenario:	*RT Low Dist.*	*Reserv. Low Dist.*	*LW Low Dist.*	*Comb. Low Dist.*	*RT High Dist.*	*Reserv. High Dist.*	*LW High Dist.*	*Comb. High Dist.*
2020-2050 Cumulative Net Flux ($MMTCO_2e$)	-156.20	-161.71	-133.98	-141.7	-69.79	-72.97	-39.61	-49.59
Forest growth	-253.37	-254.46	-278.71	-270.26	-296.5	-297.8	-295.48	-294.43
Forest mortality	47.96	48.38	52.53	51.7	44.17	44.47	49.06	47.98
Forest disturbance	15.32	15.49	14.04	14.53	77.58	95.94	69	79.73
Forest harvest	32.11	27.83	77.86	62.16	23.76	24.45	69.52	54.65
Forest salvage harvest	NA	NA	NA	NA	58.41	40.22	50.88	44.96
Active reforestation	-2.91	-2.91	-2.91	-2.91	0.00	0.00	0.00	0.00
Passive reforestation	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46
Urban tree planting	-0.30	-0.30	-0.30	-0.30	-0.02	-0.02	-0.02	-0.02
Building Development	3.80	3.69	3.38	3.44	16.27	15.43	14.45	14.59
Solar Development	2.64	2.21	2.25	2.01	8.13	6.67	6.84	6.68
2020-2050 Total Emissions	101.92	97.49	149.49	133.31	229.16	227.24	258.26	247.24
2020-2050 Total Removals	-258.11	-259.2	-283.46	-275.01	-298.95	-300.21	-297.86	-296.83

Land-Cover Change Results to 2050

The impacts of forest loss to development (building and solar) on carbon fluxes in the Integrated Scenarios align with the high and low-disturbance groupings (Table 1). The high-disturbance regime scenarios with uncoordinated land cover change all include a rate of building development area (2,748 ha/yr or 6,790 acres/yr) that is double the observed rate over the past 30 years and results in emissions ranging from 21.8 to 24.1 $MMTCO_2e$ over the 30 years (Figure 11A) or 0.73 to 0.80 $MMTCO_2e$/yr , with 14.5 to 16.3 $MMTCO_2e$ coming from direct emissions and 7.3 to 7.8 $MMTCO_2e$ from forgone sequestration. In contrast, the four low-disturbance regime scenarios with coordinated land cover change include a rate of building development (458 ha/yr or 1,132 acres/yr) that is one third the observed rate and results in emissions ranging from 4.4 to 4.7 $MMTCO_2e$ over the 30 years (Figure 11A) or 0.15 to 0.16 $MMTCO_2e$/yr , with 3.4 to 3.8 $MMTCO_2e$ coming from direct emissions and 0.9 to 1.0 $MMTCO_2e$ from forgone sequestration. Interestingly, despite the fact that building development is six times higher in the high-disturbance scenarios, direct emissions are just 4.2 to 4.7 times higher; this is because the hurricanes that co-occur in the high-disturbance scenarios reduce the average carbon density of forest that is cleared for building development. Conversely, the proportion of emissions attributed to forgone sequestration is higher in the scenarios with hurricanes due to reduced competition and increased growth.

Solar development in the high-disturbance scenarios follows recent trends patterns in terms of its siting and assumes a lower rate of electricity production per hectare, with emissions ranging from 9.7 to 12.0 $MMTCO_2e$ over the 30 years (Figure 11B) or 0.32 to 0.40 $MMTCO_2e$/yr, with 6.7 to 8.1 $MMTCO_2e$ coming from direct emissions and 3.1 to 3.8 from forgone sequestration. The low-disturbance scenarios solar siting follows conservation priorities and assumes a higher rate of electricity production per hectare; here emissions range from 2.7 to 3.3 $MMTCO_2e$ (Figure 11B) or 0.9 to 1.1 $MMTCO_2e$/yr, with 2.0 to 2.6 coming from direct emissions and 0.6 to 0.8 from forgone sequestration. In these scenarios with conservation siting criteria, a lower proportion of new solar is placed on forest cover and is instead placed on croplands with non-prime soils.

If instead of assuming immediate emissions from deforestation for building or solar development, we assume the wood enters the timber product market using the Improved Wood Utilization variant of the HWP model, over half of the emissions can be mitigated (Table 16). For example, storing some of the removed vegetation in wood products reduces the total emissions from building development through 2050 to 7.34 $MMTCO_2e$ for the Recent Trends + High Disturbance scenario, 45% of the emissions with no wood utilization (see Table 16 for additional scenarios). In the low-disturbance scenarios with less land conversion, applying Improved Wood Utilization to the Recent Trends + Low Disturbance scenario reduces building development emissions to 1.51 $MMTCO_2e$, compared to the original 3.80 $MMTCO_2e$ without any wood utilization (Table 16).

A similar pattern occurs with solar development if the removed woody vegetation enters an Improved Wood Utilization timber market. Total emissions through 2050 from solar development in the Recent Trends + High Disturbance scenario are reduced to 3.62 $MMTCO_2e$ (45% of the full emissions counterpart) (see Table 19 for additional scenarios). In the low-disturbance scenarios, the Recent Trends + Low Disturbance scenario solar development emissions are 1.18 $MMTCO_2e$, less than half of the no wood utilization counterpart (Table 16).

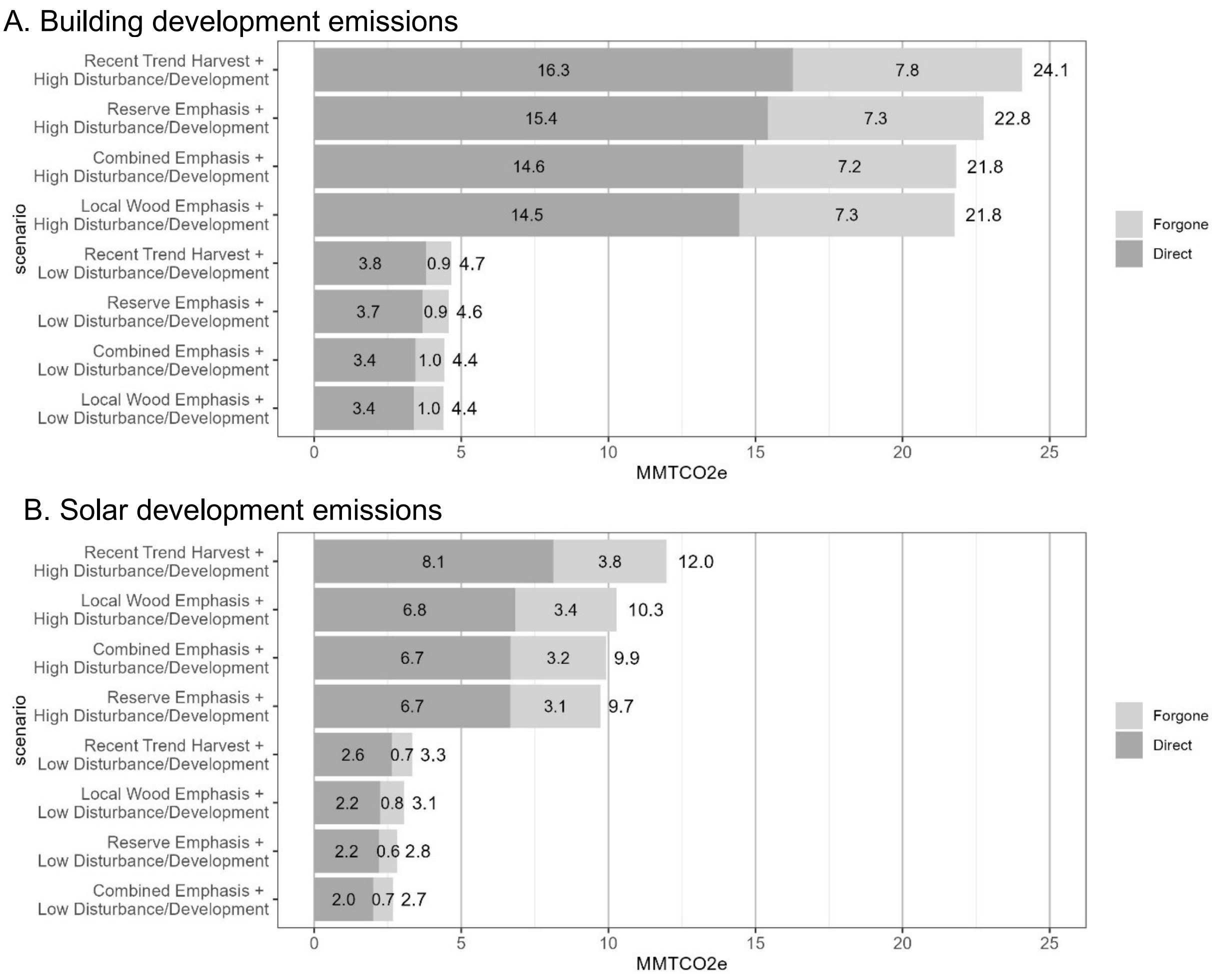

Figure 11. *Total 2020-2050 direct emissions and forgone sequestration from A. building development and B. solar development in the Integrated Scenarios.*

Table 16. *Total 2020-2050 emissions from building and solar development with no wood utilization versus improved wood utilization for each integrated scenario. High Disturbance scenarios include more land conversion, while Low Disturbance scenarios include less land conversion.*

	Building Development Emissions ($MMTCO_2e$)			**Solar Development Emissions** ($MMTCO_2e$)		
Scenario	*No wood utilization*	*Improved wood utilization*	*Wood utilization difference*	*No wood utilization*	*Improved wood utilization*	*Wood utilization difference*
Recent Trend Harvest + High Disturbance	16.27	7.34	-8.93	8.13	3.71	-4.42
Reserve Emphasis + High Disturbance	15.43	6.87	-8.56	6.67	3.04	-3.63
Local Wood Emphasis + High Disturbance	14.45	6.08	-8.37	6.84	2.96	-3.88
Combined Emphasis + High Disturbance	14.59	6.25	-8.34	6.68	2.88	-3.80
Recent Trend Harvest + Low Disturbance	3.80	15	-2.25	2.64	1.018	-1.46
Reserve Emphasis + Low Disturbance	3.69	1.47	-2.22	2.21	0.98	-1.23
Local Wood Emphasis + Low Disturbance	3.38	1.30	-2.08	2.25	0.89	-1.36
Combined Emphasis + Low Disturbance	3.44	1.37	-2.07	2.01	0.84	-1.17

The effects of increasing forest and tree cover from reforestation and tree planting on carbon fluxes align with the high and low-disturbance groupings in the Integrated Scenarios (Figure 16). The high-disturbance regime scenarios with uncoordinated land cover change include only baseline rates of reforestation and tree planting, with passive reforestation occurring on 6,581 ha and urban tree planting occurring on 1,619 ha (182,820 trees), removing a total of 1.5 $MMTCO_2e$ from 2020 to 2050. In contrast, the four low-disturbance regime scenarios with coordinated land cover change include active reforestation of 19,740 ha, and urban tree planting on 41,212 ha (4,625,490 trees) from 2020 to 2050, in addition to the baseline, removing a total of 3.2 $MMTCO_2e$. Although reforestation constitutes only 32% of the total land area with new tree and forest cover, it yields a much larger carbon benefit than urban tree planting due to much higher tree densities, removing 2.9 $MMTCO_2e$ (91%) in the coordinated land cover change scenarios (Figure 16).

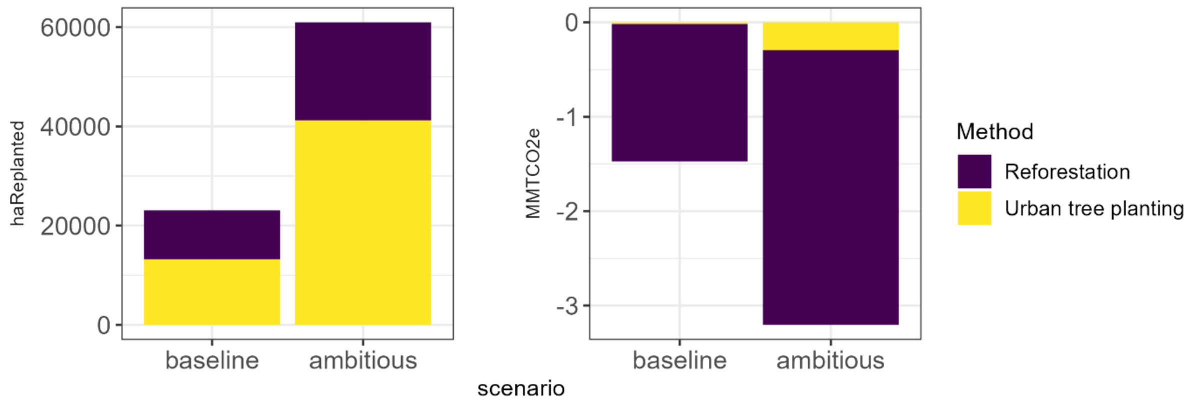

Figure 16. *Reforestation and tree planting land area and carbon flux from 2020 to 2050 under uncoordinated and coordinated land-cover change scenarios. Uncoordinated land cover change (associated with the "High Disturbance" integrated scenarios) include only baseline levels of reforestation and tree planting, while coordinated land-cover change (associated with "Low Disturbance" integrated scenarios) includes ambitious levels of reforestation and tree-planting i.e. occurring on 25% of suitable land by 2050.*

Forest Carbon Results to 2100

When we model the Integrated Scenarios out to 2100, retaining harvesting but excluding development-driven land conversion, the cumulative net carbon flux ranged from –305.52 to -195.01 $MMTCO_2e$ (Figures 17 and 18), equivalent to an annual average of –3.82 to –2.44 $MMTCO_2$/yr. The low disturbance group's mean annual flux ranged from -5.89 to -4.72 $MMTCO_2e$/yr for 2020-2025 and -1.05 to -0.24 $MMTCO_2e$/yr for 2095-2100, whereas in the high disturbance group, the mean annual flux ranged from -5.89 to -4.73 $MMTCO_2e$/yr for 2020-2025 and –1.06 to -0.25 for 2095-2100 (Table 17). For further comparison, in 2100, under the high disturbance scenarios, the cumulative net emissions ranges from –195.01 to –250.57, spanning 55 $MMTCO_2e$, compared to the low disturbance scenarios with a range of –300.85 to –305.52, a span of only 4.66 $MMTCO_2e$.

All scenarios, except the two using Recent Trends harvesting, applied the climate-oriented harvest prescriptions (Table 1). On average, these harvests removed less than 50% of the carbon per-unit-area as the conventional Recent Trends prescriptions (95.4 MTCO2e/ha versus 234.9 MTCO2e/ha). Therefore, meeting the same target harvest volumes required double the harvest area. This expansion of harvested area made it difficult to achieve the volume targets in the Local Wood Emphasis scenario (i.e. 20% of 2020 consumption, or 10.36 MMT of wood biomass or 38.04 MMTCO2e). Where Recent Trends harvested 251,000 hectares in 30 years and provided approximately 7% of consumption, the Local Wood Emphasis scenario harvested (less intensely) on 1,079,500 hectares to provide 20% of consumption. The integrated nature of the scenarios (i.e., the fact that the area harvested and the prescriptions are changed together) makes it difficult to precisely parse the carbon effects of the climate-oriented harvest prescriptions from the changes in total harvest volume. Nonetheless, it is known that partial harvesting can increase the rate of tree growth (and carbon sequestration) in the remaining trees by increasing the available growing space (D'Amato et al. 2011). However, partial harvesting also lowers live carbon stocks and much of the carbon stored within harvested trees is emitted during processing or disposal. Among the 80-year forest management scenarios, those with higher levels of timber harvest (i.e., Local Wood and Combined) increased tree growth through mid-century, but also increased emissions; therefore, the net result was less net carbon sequestration than in the scenarios with lower harvest volumes (i.e., Reserve Emphasis and Recent Trends). By 2100, however, benefits of the climate-oriented harvest prescriptions on biomass accrual are apparent, and the Local Wood Emphasis and Combined Emphasis scenarios show relatively smaller differences in cumulative net flux compared to the Reserve Emphasis scenario, particularly in the low-disturbance scenarios (Figure 17).

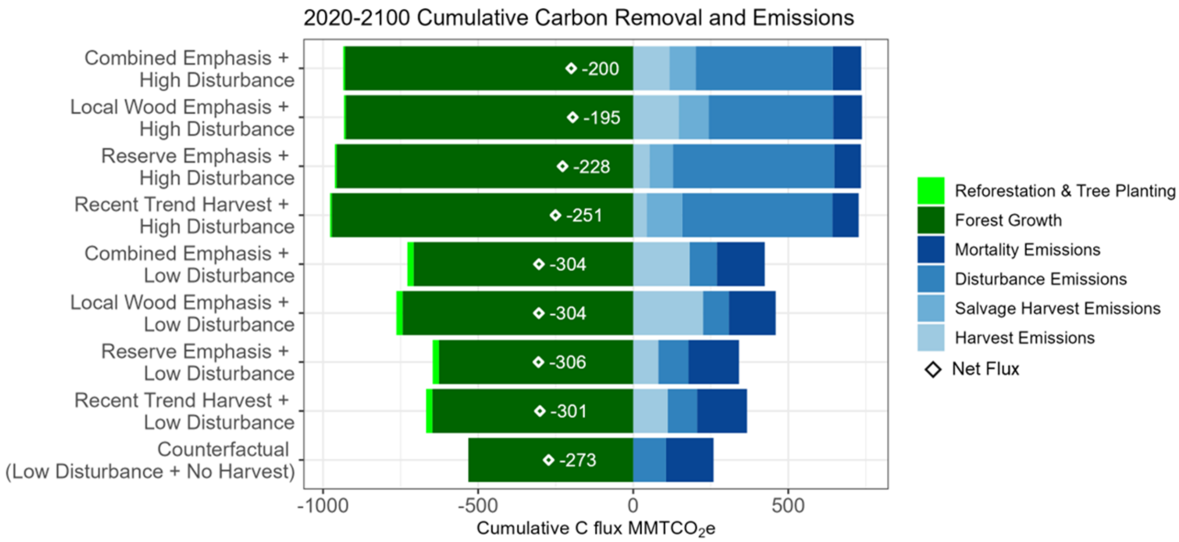

Figure 17. *Cumulative fluxes of forest carbon between 2020 and 2100 for each of the eight Integrated Scenarios and a counterfactual scenario (no harvesting). Green bars to the left represent cumulative removals (i.e. sequestration), blue bars to the right represent cumulative emissions, and white diamonds show the cumulative net flux to the atmosphere. Carbon transfers between all simulated pools are accounted for, including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills). For consistency across time, these results do not include the effects of development-driven land conversion because development was not simulated past 2050. Note that the "High Disturbance" scenarios include major hurricanes in 2038 and 2054.*

Table 17. *Summary of carbon fluxes (MMTCO$_2$e) for each of the Integrated Scenarios over the 2020-2100 modeled time period. Flux attribution (e.g. to forest harvest or disturbances) reflects direct emissions only, not indirect effects (e.g. growth enhancement or reduced mortality), which are accounted for in the Forest growth and Forest mortality rows. Scenario forest management regimes are abbreviated as follows: RT = Recent Trends, Reserv. = Reserve Emphasis, LW = Local Wood Emphasis, Comb. = Combined Emphasis. Disturbance regimes are abbreviated as Low Dist. = Low Disturbance and High Dist. = High Disturbance.*

Scenario:	*RT Low Dist.*	*Reserv. Low Dist.*	*LW Low Dist.*	*Comb. Low Dist.*	*RT High Dist.*	*Reserv. High Dist.*	*LW High Dist.*	*Comb. High Dist.*
2020-2100 Cumulative Net Flux (MMTCO$_2$e)	-300.85	-305.52	-304.28	-303.96	-250.57	-227.82	-195.01	-199.83
Forest growth	-647.44	-626.21	-743.28	-707.76	-971.57	-956.15	-926.64	-928.95
Forest mortality	160.96	162.84	151.05	154.79	84.68	86.04	92.96	91.71
Forest disturbance	94.61	97.02	83.43	87.45	484.23	520.3	400.84	442.14
Forest harvest	111.36	81.18	224.87	181.91	43.39	52.54	146.83	116.77
Forest salvage harvest	NA	NA	NA	NA	114.58	75.33	96.87	84.39
Active reforestation	-15.27	-15.271	-15.27	-15.27	0.00	0.00	0.00	0.00
Passive reforestation	-5.74	-5.74	-5.74	-5.74	-5.74	-5.74	-5.74	-5.74
Urban tree planting	-3.15	-3.15	-3.15	-3.15	-0.14	-0.14	-0.14	-0.14
Building Development	NA	NA	-NA	NA	NA	NA	NA	NA
Solar Development	NA	NA	NA	NA	NA	NA	NA	NA
2020-2100 Total Emissions	366.93	341.04	459.35	424.15	726.88	734.2	737.51	735
2020-2100 Total Removals	-667.78	-646.55	-763.62	-728.10	-977.45	-962.03	-932.52	-934.83
2020-2100 Mean Annual Net Flux	-3.76	-3.82	-3.80	-3.80	-3.13	-2.85	-2.44	-2.50
2020-2025 Mean Annual Net Flux	-5.68	-5.89	-4.73	-5.11	-5.68	-5.86	-4.70	-5.09
2095-2100 Mean Annual Net Flux	-0.36	-0.25	-1.06	-0.84	0.66	0.54	-0.46	-0.14

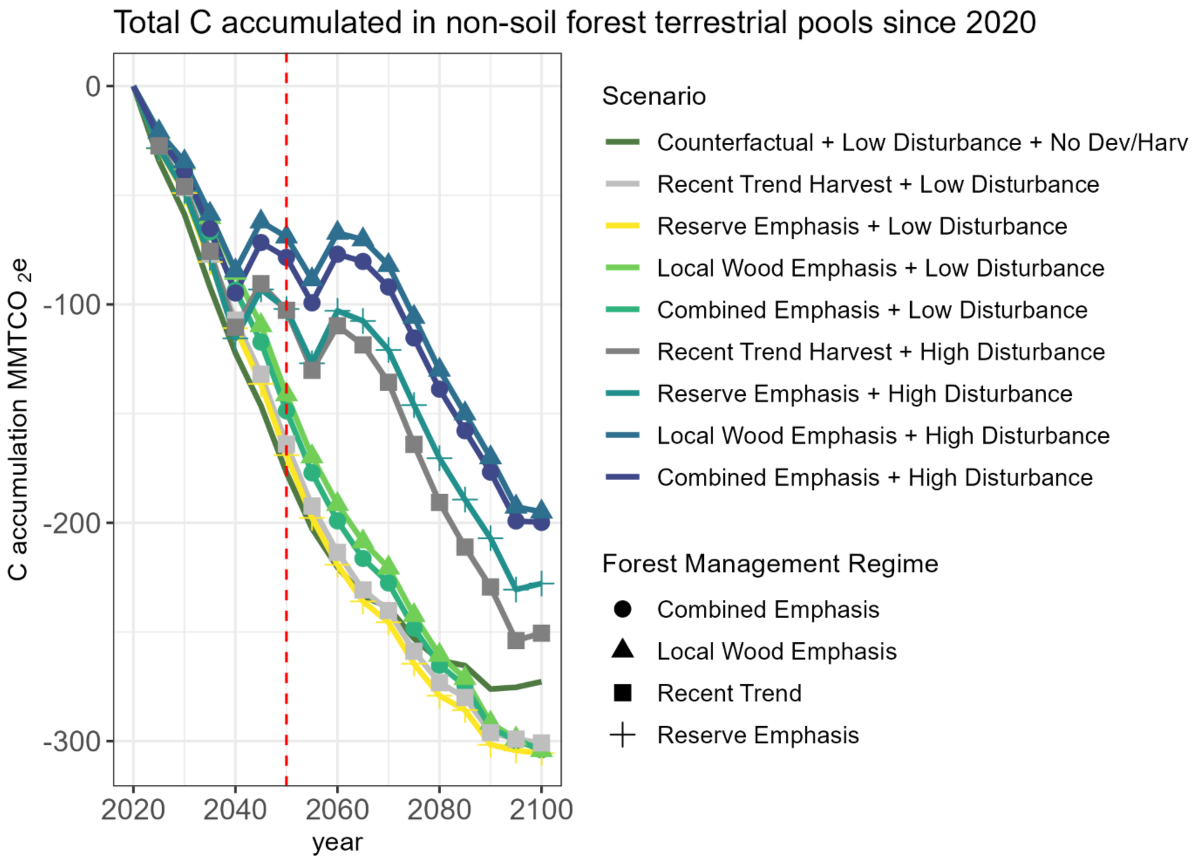

Figure 18. *Total accumulation of carbon from 2020 to 2100 in all non-soil carbon pools (including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills). Negative values indicate cumulative carbon removal from the atmosphere (i.e. cumulative negative emissions). For consistency across time, these results do not include the effects of development-driven land conversion because development was not simulated past 2050. Note that the "High Disturbance" scenarios include major hurricanes in 2038 and 2054. Red dash line indicates 2050, Massachusetts' net zero compliance year.*

While total net carbon emissions by 2100 did not show large differences when grouped by low- and high-disturbance, the annual net sequestration was quite variable by scenario and over time (Figure 19; Appendix Table A8). In particular, in the high-disturbance scenario, hurricanes caused large variations in net emissions, including some five-year periods resulting in net emissions. Following the hurricanes in each of the high-disturbance scenarios, there is increased growth in the remaining forest, resulting in higher levels of sequestration in the latter half of the century than the low-disturbance scenarios. In the low-disturbance scenarios, the lack of high-intensity disturbance results in more of the forest reaching a stage when emissions from natural mortality balances sequestration. In particular, scenarios with less harvest show higher emissions from natural mortality, but scenarios with higher rates of harvest, higher emissions are associated with that harvesting. Additionally, in the low disturbance scenarios, the combined emissions from gap-scale disturbance and modeled insect pests, along with natural mortality, are greater than those from harvesting alone, particularly toward the end of the century (Figure 19). Note, however, that the results at the end of the century are more highly influenced by LANDIS/PnET model mechanisms and assumptions, so while these results represent a well-supported estimate of future forest processes, the uncertainty around these estimates increases further along in the simulation.

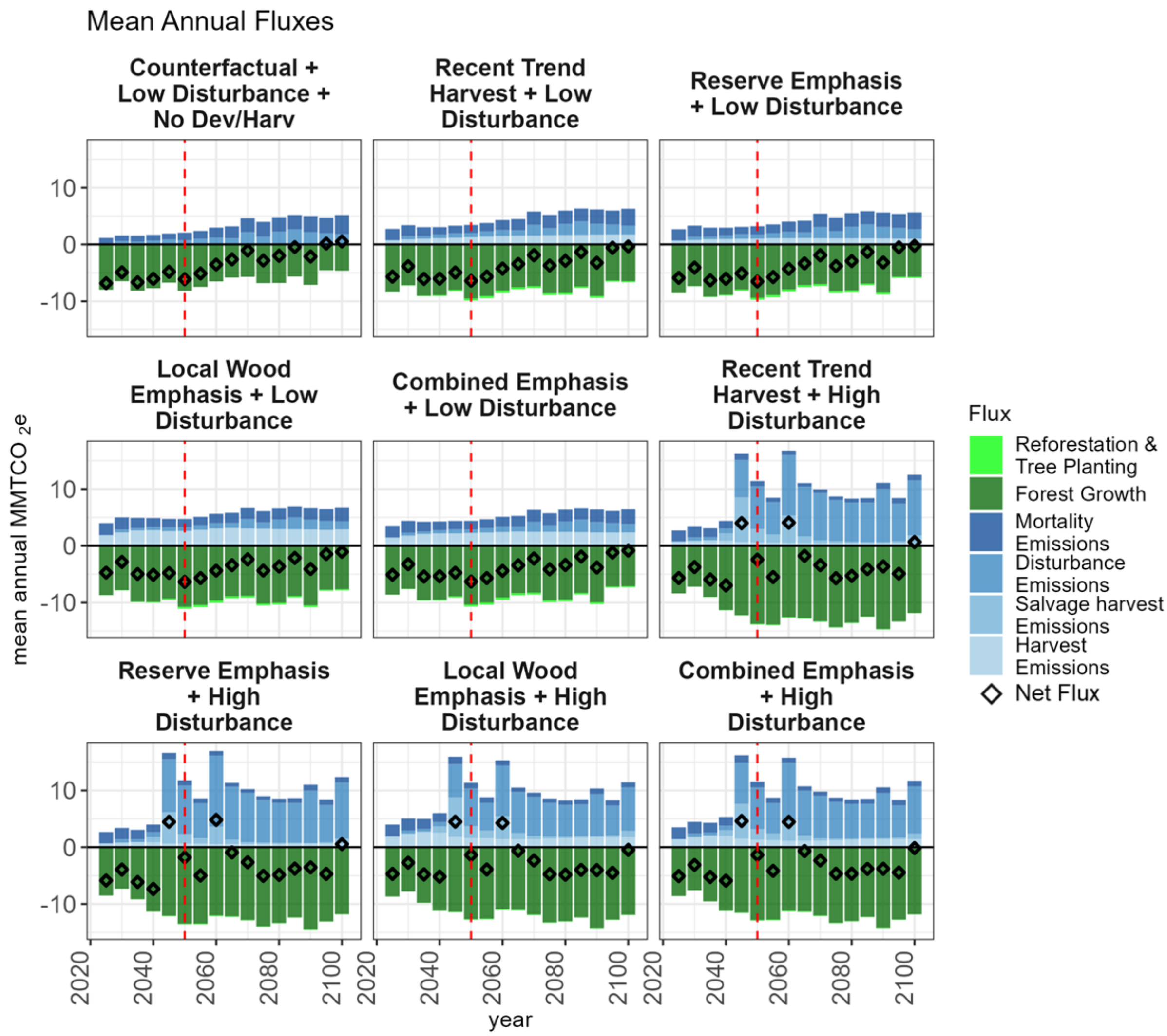

Figure 19. *Mean annual carbon fluxes to the atmosphere over 5-year timesteps from 2020 to 2100 for a counterfactual scenario (no development or harvesting) and the eight Integrated Scenarios. Green bars below zero represent carbon removals (i.e. sequestration), blue bars above zero represent emissions, and black diamonds show the net flux to the atmosphere (i.e. the annualized difference between sequestration and emissions in a timestep). For consistency across time, these results do not include the effects of development-driven land conversion because development was not simulated past 2050. Note that the "High Disturbance" scenarios include major hurricanes in 2038 and 2054. Red dash line indicates 2050, Massachusetts' net zero compliance year.*

Harvested Wood Product Results

For each of the Integrated Scenarios, different amounts and types of harvested wood products (short and long-term) were produced based on the species and size classes removed in each scenario (Table 18, Figure 19). For these results we used the long-term scenarios with no land cover change (see Figure 19). Overall, the Local Wood Emphasis scenarios produced the most stored carbon from harvest, as was the intent of the scenario, but also had the highest emissions from harvesting. In 2050, the low-disturbance Local Wood Emphasis scenario had 73.25 $MMTCO_2e$ stored in a combination of products in use, solid waste disposal sites, and logging residues in the forest, while 51.02 $MMTCO_2e$ was emitted into the atmosphere from short-term wood product production, use, and disposal (e.g., paper products, firewood) and logging residue decay. By the end of the century, the same scenario had 141.66 $MMTCO_2e$ stored and 155.54 $MMTCO_2e$ emitted. Comparatively, the Recent Trends in harvesting scenario had 32.49 $MMTCO_2e$ stored and 21.07 $MMTCO_2e$ emitted in 2050, and 71.46 $MMTCO_2e$ stored and 77.00 $MMTCO_2e$ emitted in 2100.

The high-disturbance scenarios were more complex with salvage logging efforts post-hurricane creating pulses of additional harvested wood products, especially in the first half of the century (Figure 19). For example, in 2050 the Recent Trends + High Disturbance scenario had 16.81 $MMTCO_2e$ (52%) more carbon stored in harvested wood products, disposal sites, and residues than the low-disturbance Recent Trends counterpart and 12.28 $MMTCO_2e$ (58%) more harvesting emissions than the low-disturbance counterpart. By the end of the century, though, the Recent Trends + High Disturbance scenario had 12.84 $MMTCO_2e$ (18%) less stored and only 1.27 $MMTCO_2e$ (2%) fewer emissions, likely due to differences in wood quality and species differences in salvaged wood as compared to harvesting. The Local Wood Emphasis scenario followed a similar pattern to Recent Trends, but less pronounced with the already higher levels of harvest.

Table 18. *Total stored and emitted carbon ($MMTCO_2e$) pools associated with harvested wood products, assuming Recent Trends in wood utilization.*

Scenario	2050 total stored carbon	2050 total emitted carbon	2100 total stored carbon	2100 total emitted carbon
Recent Trend Harvest + High Disturbance	49.31	33.35	58.63	75.73
Reserve Emphasis + High Disturbance	41.15	27.59	53.88	66.33
Local Wood Emphasis + High Disturbance	82.00	60.11	115.68	141.11
Combined Emphasis + High Disturbance	67.60	48.31	94.76	114.96
Recent Trend Harvest + Low Disturbance	32.49	21.07	71.46	77.00
Reserve Emphasis + Low Disturbance	27.02	18.10	49.36	56.39
Local Wood Emphasis + Low Disturbance	73.25	51.02	141.66	155.54
Combined Emphasis + Low Disturbance	60.04	40.45	115.24	125.60

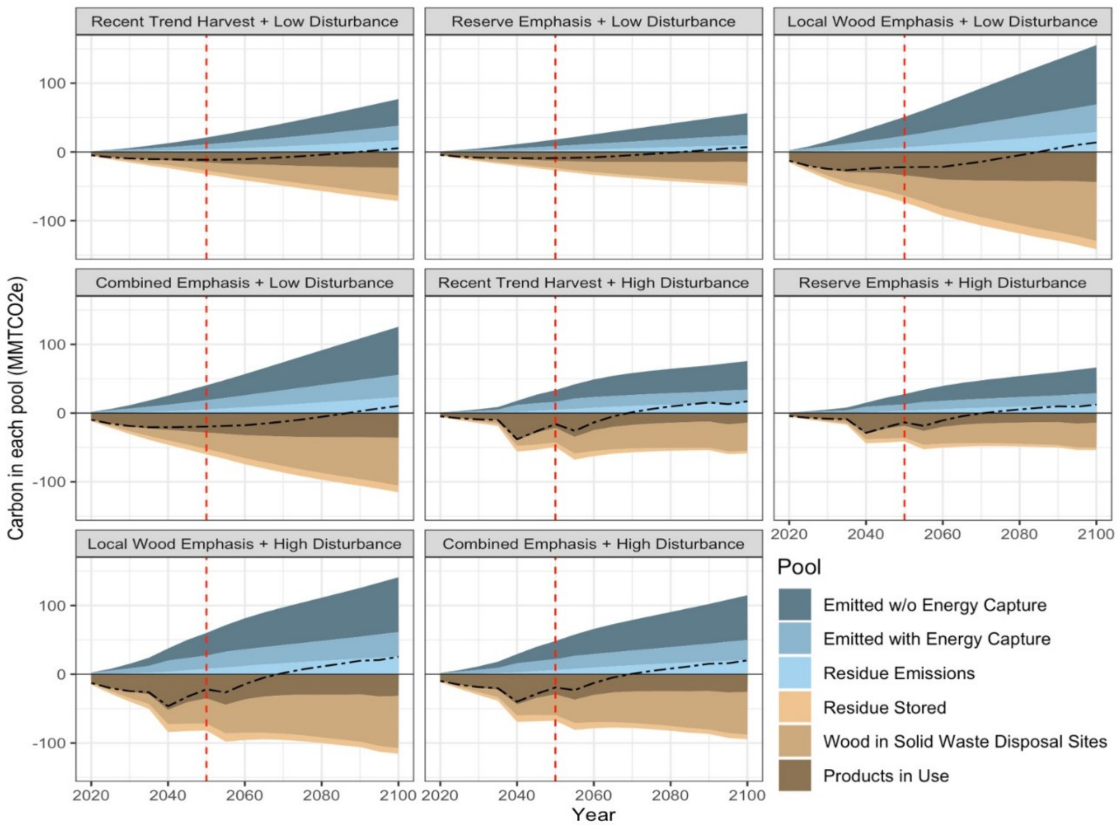

Figure 19. *Harvested wood product carbon storage (brown shaded areas) and atmospheric emission (blue shaded areas) pools for the Recent Trends Wood Utilization variant of the eight Integrated Scenarios. Values reflect simulated new carbon transfers into and out of these pools between 2020 and 2100. Residues represent both logging and mill residue storage and emission pools (wood left on site or at the mill during the wood product production process). The red dashed line represents 2050 and the black dashed line represents the balance between stored carbon and emitted carbon through time.*

The Improved Wood Utilization HWP variant of the HWP model resulted in similar results to the scenarios with the Recent Trends in Wood Utilization variant, but with a shift towards more wood in longer-term products and a decrease in emissions (Table 19, Figure 20). For example, the low-disturbance Recent Trends in harvesting scenario coupled with the Improved Wood Utilization HWP variant (Figure 21) resulted in 3.38 $MMTCO_2e$ (16%) fewer harvesting emissions than its Recent Trends HWP counterpart in 2050 (Figure 20). Similarly, the Improved Wood Utilization variant resulted in 3.37 $MMTCO_2e$ (19%) fewer emissions for the Reserves Emphasis scenario, 9.40 $MMTCO_2e$ (18%) fewer emissions for the Local Wood Emphasis scenario, 7.45 $MMTCO_2e$ (18%) fewer emissions for the Combined Emphasis scenario, all in 2050. The differences in emissions carried through to 2100 (Table 19).

Table 19. *Total stored and emitted carbon (MMTCO$_2$e) pools associated with harvested wood products, assuming Improved Wood Utilization.*

Scenario	2050 total stored carbon	2050 total emitted carbon	2100 total stored carbon	2100 total emitted carbon
Recent Trend Harvest + High Disturbance	119.29	54.34	145.67	139.22
Reserve Emphasis + High Disturbance	90.61	40.78	114.09	104.94
Local Wood Emphasis + High Disturbance	149.11	72.42	201.52	182.46
Combined Emphasis + High Disturbance	126.03	59.97	168.28	152.06
Recent Trend Harvest + Low Disturbance	35.88	17.68	82.92	65.55
Reserve Emphasis + Low Disturbance	30.39	14.73	59.41	46.34
Local Wood Emphasis + Low Disturbance	82.64	41.62	166.90	130.30
Combined Emphasis + Low Disturbance	67.50	32.99	135.72	105.12

The high-disturbance scenarios had pronounced reductions in disturbance emissions when simulating Improved Wood Utilization, due to the shift from 25% salvage logging in the Recent Trends in wood utilization HWP scenario, to 75% salvage logging in the Improved Wood Utilization HWP variant (Figure 21). However, the reduction in disturbance emissions due to salvage logging resulted in increases in salvage harvesting emissions, therefore both the increase in salvage harvesting emissions and reduction in disturbance emissions are reported side-by-side. In 2050, the Improved Wood Utilization variant of the HWP model resulted in 23.59 MMTCO$_2$e more salvage harvesting emissions and 28.96 MMTCO$_2$e fewer disturbance emissions in the Recent Trends + High Disturbance scenario (-5.37 MMTCO$_2$e change in net emissions), 16.04 MMTCO$_2$e more salvage harvesting emissions and 19.73 MMTCO$_2$e fewer disturbance emissions in the Reserves Emphasis + High Disturbance scenario (-3.69 MMTCO$_2$e change in net emissions), 20.58 MMTCO$_2$e more salvage harvesting emissions and 25.27 MMTCO$_2$e fewer disturbance emissions in the Local Wood Emphasis + High Disturbance scenario (-4.69 MMTCO$_2$e change in net emissions), and 18.08 MMTCO$_2$e more salvage harvesting emissions and 22.22 MMTCO$_2$e fewer disturbance emissions in the Combined Emphasis + High Disturbance scenario (-4.14 MMTCO$_2$e net emissions) in 2050 (Figure 21).

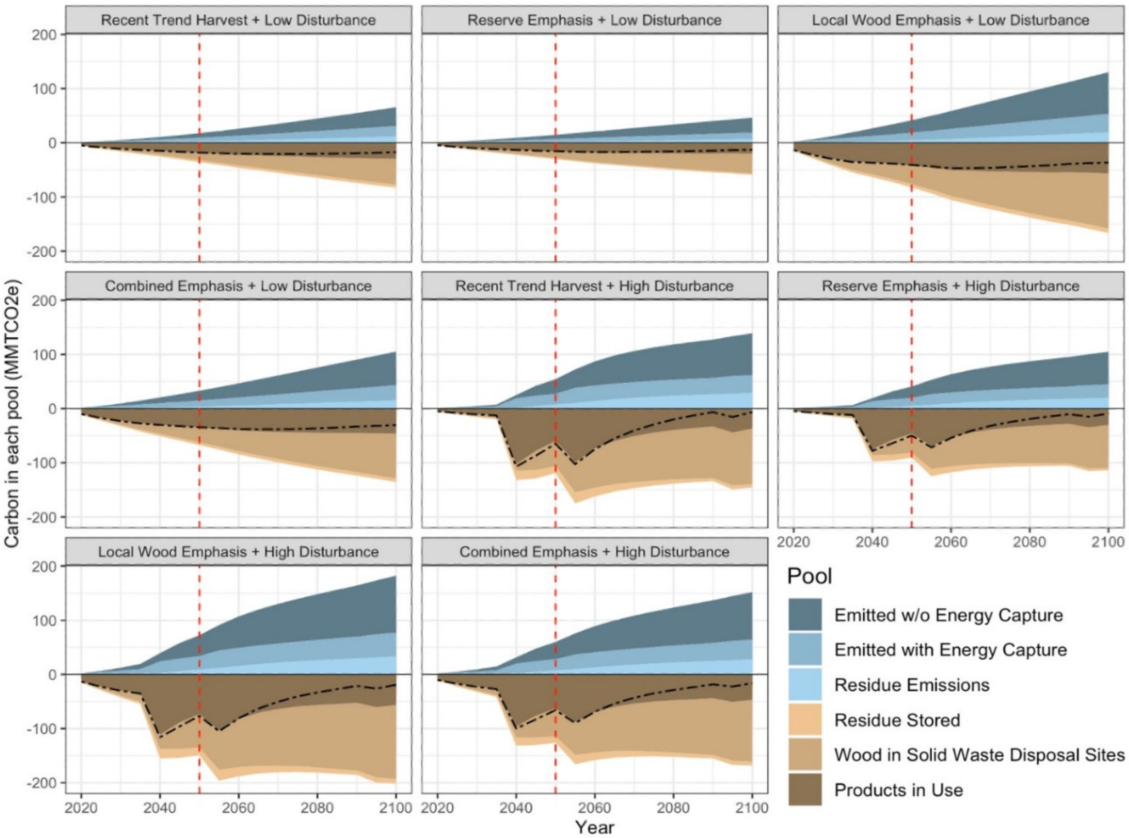

Figure 20. *Harvested wood product carbon storage (brown shaded areas) and atmospheric emissions (blue shaded areas) pools for the Improved Wood Utilization variant of the eight Integrated Scenarios. Values reflect simulated new carbon transfers into and out of these pools between 2020 and 2100. Residues represent both logging and mill residue storage and emission pools (wood left on site or at the mill during the wood product production process). The red dashed line represents 2050 and the black dashed line represents the balance between stored carbon and emitted carbon through time.*

Again, trends continued into 2100 with 67.94 MMTCO$_2$e more salvage harvesting emissions and 124.26 MMTCO$_2$e fewer disturbance emissions in the Recent Trends + High Disturbance scenario (-56.32 MMTCO$_2$e change in net emissions), 44.49 MMTCO$_2$e more salvage harvesting emissions and 81.95 MMTCO$_2$e fewer disturbance emissions in the Reserves Emphasis + High Disturbance scenario (-37.46 MMTCO$_2$e change in net emissions), 57.77 MMTCO$_2$e more salvage harvesting emissions and 105.98 MMTCO$_2$e fewer disturbance emissions in the Local Wood Emphasis + High Disturbance scenario (-48.21 MMTCO$_2$e net emissions), and 50.18 MMTCO$_2$e more salvage harvesting emissions and 92.29 MMTCO$_2$e fewer disturbance emissions in the Combined Emphasis + High Disturbance scenario (-42.11 MMTCO$_2$e net emissions) (Figure 21).

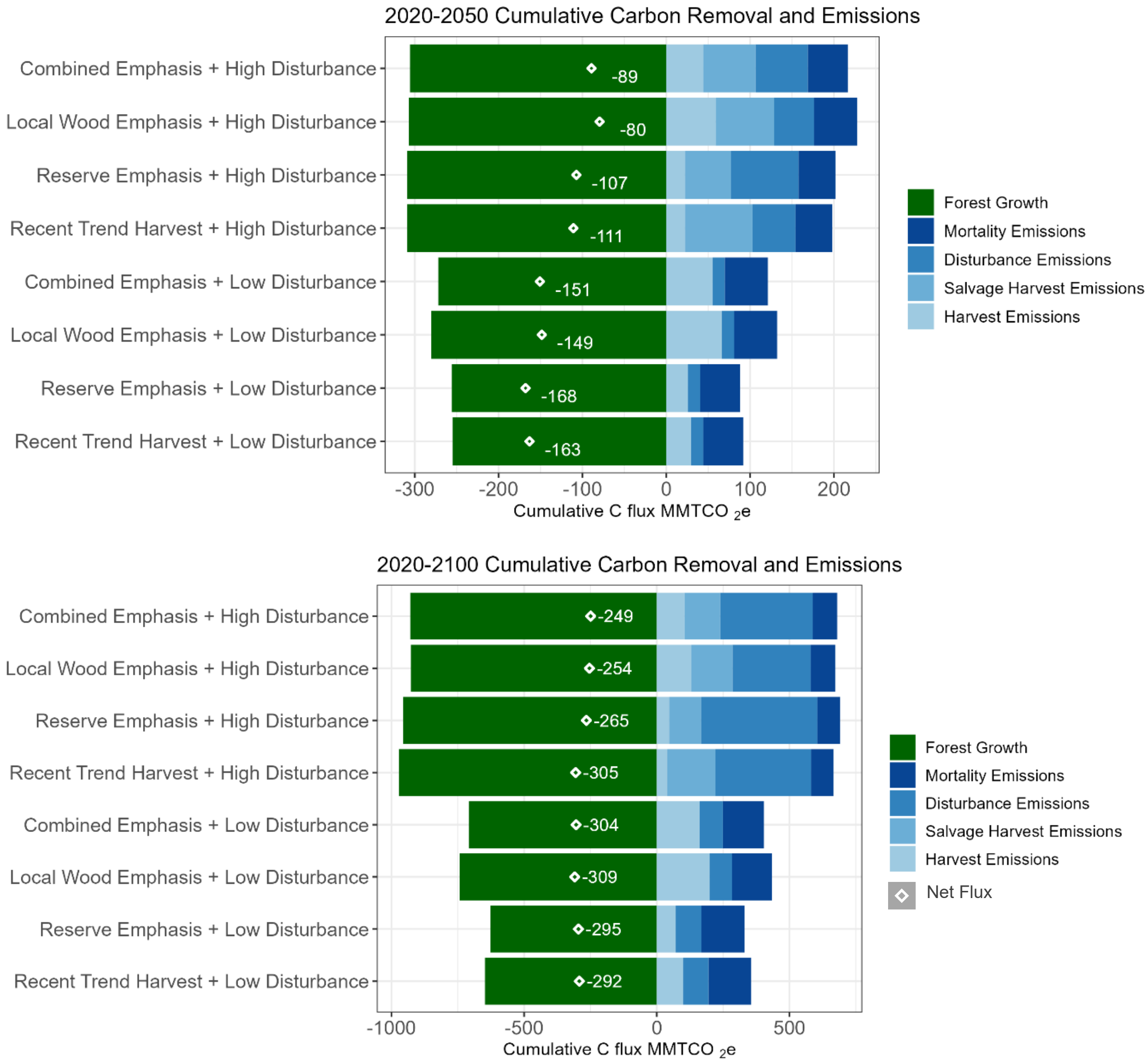

Figure 21. *Cumulative fluxes of carbon between 2020 and 2050 (top panel) and between 2020 and 2100 (bottom panel) for the Improved Wood Utilization variant of each of the eight Integrated Scenarios. Green bars to the left represent cumulative removals (i.e. sequestration), blue bars to the right represent cumulative emissions, and white diamonds show the cumulative net flux to the atmosphere. Carbon transfers between all simulated pools are accounted for, including in-forest live and dead wood and harvest residues, new forest and tree live wood, and out-of-forest wood products in use and in landfills). Note that these results do not include the effects of land cover change, and the "High Disturbance" scenarios include major hurricanes in 2038 and 2054.*

Each of the different harvesting scenarios produced a different amount of harvested wood products (both long- and short-term). Due to these differences, they would each meet different amounts of the wood product demand for Massachusetts, as well as create different pressures on wood production outside of the state. Most of the scenarios produced a similar or increasing amount of wood products as the Recent Trends in harvest scenario, since the objective was to limit the amount of leakage of harvesting to outside of the state (Figure 22). To calculate the leakage or the additional production in each scenario, we differenced the total amount of products created in the Recent Trends with the total products created in the alternative scenarios. This difference represents the additional wood product demand that can be met within the scenario, or the potential leakage in the scenario.

By 2050, the Local Wood and Combined scenarios produced more wood products than the Recent Trends scenario. In the Recent Trends HWP variant of the Reserves Emphasis scenario produced 5.42 $MMTCO_2e$ less wood products than the Recent Trends in harvesting scenario (Figure 22). In contrast, the Local Wood Emphasis scenario produced 63.37 $MMTCO_2e$ more products by 2050, potentially alleviating some of the demand for wood products produced outside of the Commonwealth. In the high-disturbance scenarios, the products produced are slightly less, where the Reserves Emphasis + High Disturbance scenario produced 11.04 $MMTCO_2e$ fewer products than the Recent Trends Harvest + High Disturbance scenario for the Recent Trends variant of the HWP model (Figure 22). Similarly, the Local Wood Emphasis + High Disturbance scenario produced 52.79 $MMTCO_2e$ more products.

The Improved Wood Utilization variant of the HWP emphasizes the differences between the scenarios, particularly when post-hurricane salvage logging is part of the scenario. For example, in the low-disturbance Recent Trends in harvesting scenario, applying the Improved Wood Utilization HWP variant resulted in 2.57 $MMTCO_2e$ more products by 2050 than the Recent Trends HWP variant (Figure 22). The Local Wood Emphasis scenario with the Improved Wood Utilization HWP variant resulted in 68.87 $MMTCO_2e$ more products created by 2050 than the Recent Trends Harvest with Recent Trends HWP variant. In the high-disturbance scenarios, applying the Improved Wood Utilization HWP variant resulted in 81.75 $MMTCO_2e$ more products for the Recent Trend Harvest + High Disturbance scenario by 2050. Similarly, the Improved Wood Utilization HWP variant resulted in 127.09 $MMTCO_2e$ more products for the Local Wood Emphasis + High Disturbance by 2050 than the Recent Trends Harvest + High Disturbance scenario with the Recent Trends HWP variant. Most of the additional products in use are a result of the additional salvage logging efforts following major hurricane disturbances. By 2100, the differences in the scenarios' harvested wood product creation was more pronounced though the scenarios followed the same patterns (Figure 22).

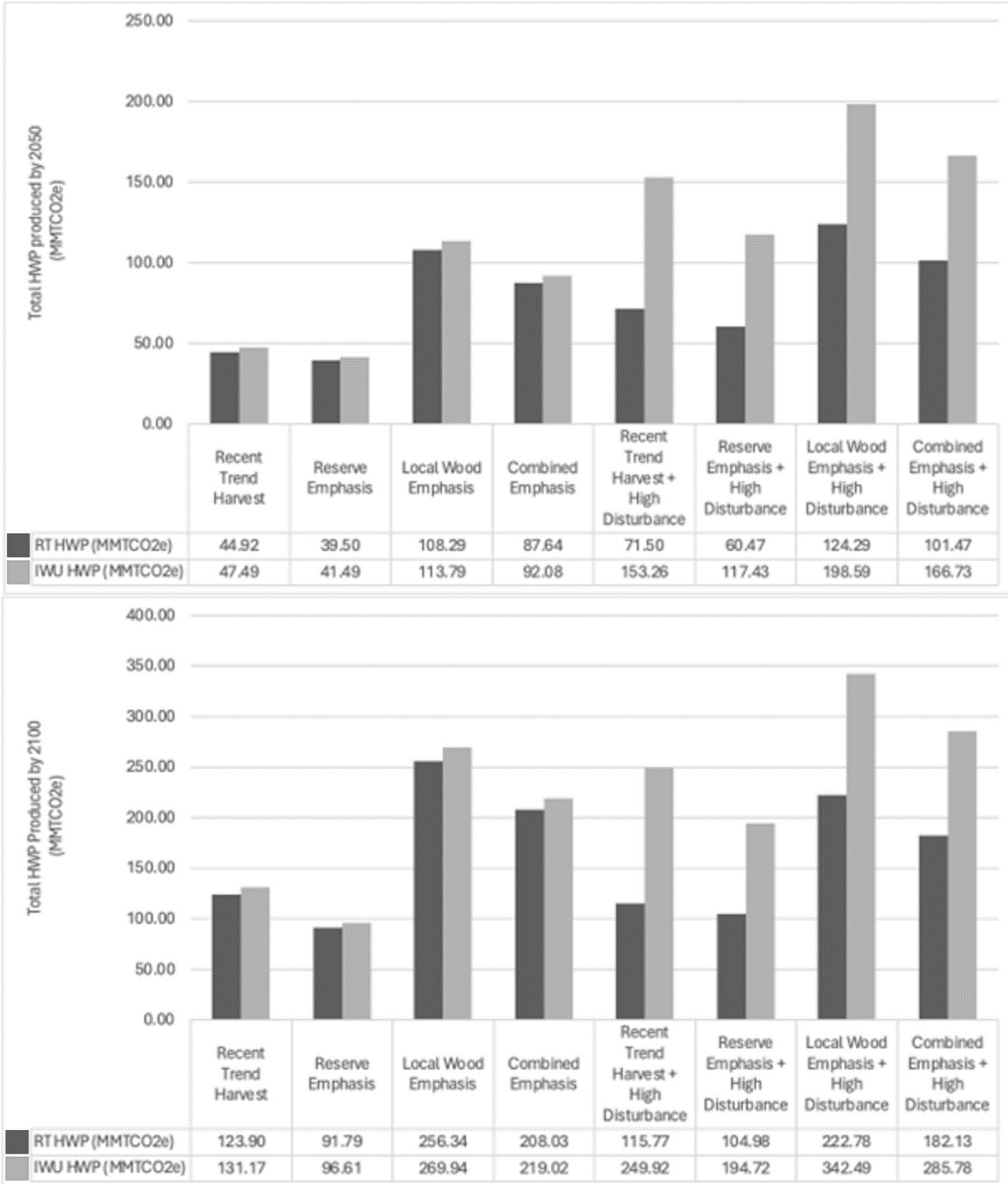

Figure 22. *Sum of all wood products created from 2020 to 2050 (top panel) and 2020 to 2100 (bottom panel) for the Recent Trends (RT HWP, dark gray bars) and the Improved Wood Utilization Harvested Wood Products (IWU HWP, light gray bars) variant of each of the Integrated Scenarios.*

4.2 Focus Scenario Results

To isolate impacts of specific land uses on forest and terrestrial carbon, we simulate a counterfactual scenario that excludes that land use then compare it to a scenario with it included. For example, to quantify the impact of land-cover change we compare a simulation that includes all land uses and ecological processes to one that includes the ecological processes (i.e., forest growth and low ecological disturbances) and timber harvesting, but does not include land-cover change. The difference between these two simulations is the impact of land-cover change (see Table 14B). We emphasize that the carbon accumulation rates in the counterfactual scenarios are not realistic policy options, but these scenarios are essential to gauge the impact and magnitude of the Focus Scenarios.

Using this approach, we simulate a counterfactual scenario to estimate the theoretical biophysical potential for Massachusetts' existing forests to sequester and store additional carbon between 2020 and 2050 in the absence of land conversion, harvesting, and major disturbances. Under this counterfactual scenario, carbon stocks increase by 177.0 $MMTCO_2e$. In a simulation that includes a continuation of recent trends in land use (i.e., land cover change and timber harvesting) and non-hurricane disturbances, carbon stocks increase by 147.8 $MMTCO_2e$ between 2020 and 2050. The difference between the counterfactual and the recent trends in land use is 29.2 $MMTCO_2e$ by 2050—or an average of 1.0 $MMTCO_2e$ per year—and represents the additional theoretical carbon sequestration and storage our current forests could provide. In other words, if recent trends in land use continue to 2050, the emissions from development and harvesting would reduce net sequestration by 20%. Permanent forest loss for building and solar development accounts for approximately half of this difference, while the remaining half is attributable to timber harvesting (accounting for carbon storage in wood products and landfills). This constitutes a relatively modest potential increase over current level of NWL carbon sequestration (7.1 $MMTCO_2e$, including non-forest ecosystems), not nearly enough to fully offset the 14 $MMTCO_2e$ of allowable residual emissions in 2050 under the Massachusetts Net Zero emissions limit (EEA 2022)..

Building Development Results

In addition to the Recent Trends scenarios, we examined three alternative Building Focus Scenarios and estimated the impact on terrestrial carbon by comparing each scenario to a Counterfactual (no development) scenario with no new development for buildings or solar (Table 7), with all scenarios including forest ecosystem dynamics, including gap scale disturbances, and recent trends harvesting. As such, these results include estimates of direct carbon emissions associated with the land clearing and of foregone carbon sequestration where forest clearing for building development occurred (i.e. sequestration that would have occurred if the land remained forest). The spatial distribution of building development under each scenario is shown in Figure 23, and emissions and live carbon accumulation are shown in Figures 24 and 25.

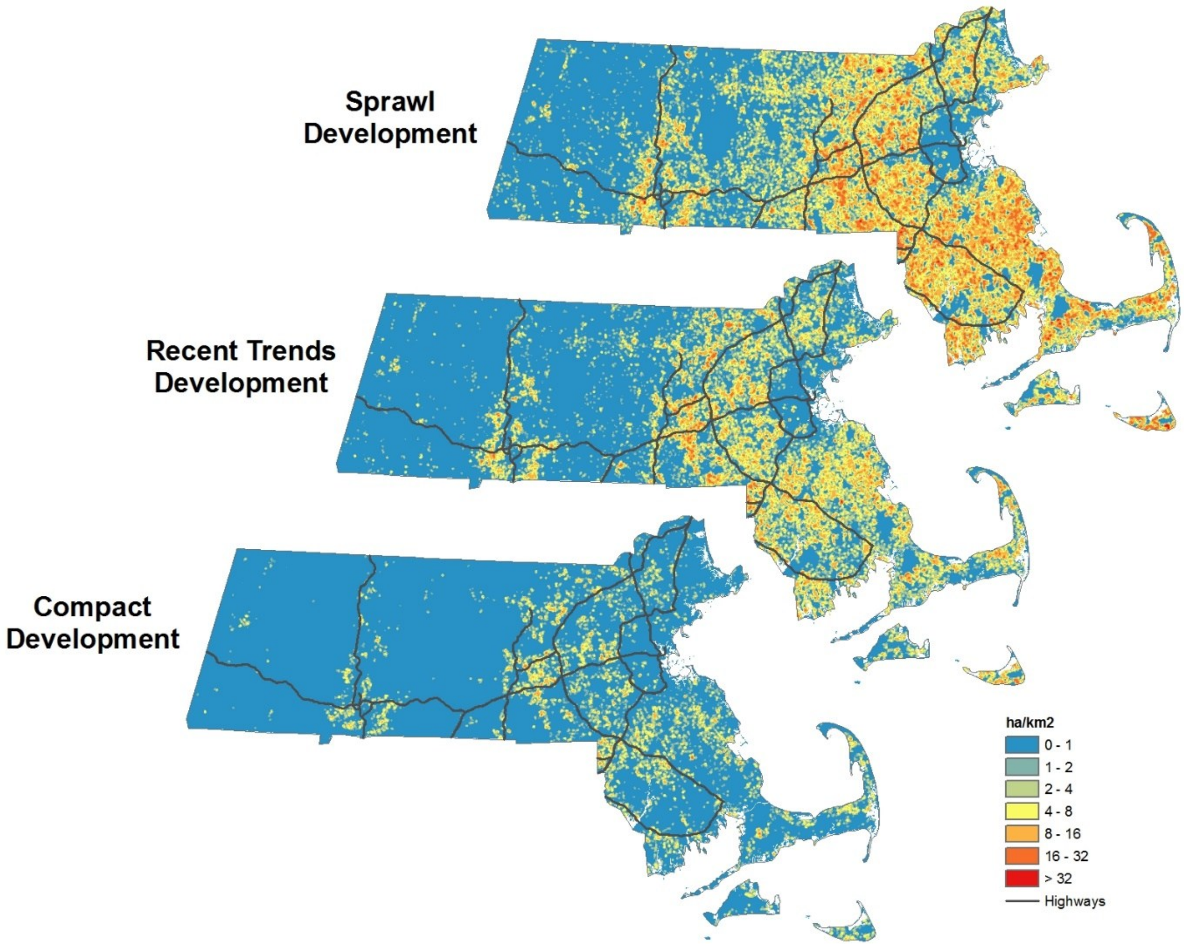

Figure 23. *Spatial distribution of greenfield building development. The Sprawl Development and Compact Development were used the Integrated Scenarios. All three were analyzed in the Focus Scenarios. Data has been smoothed for visualization using a 10 km moving window showing hectares of new development per square kilometer.*

The Recent Trends scenario replicates the annual rate of greenfield building development seen in the 2000-2020 reference period. In this scenario, live carbon increases by 95.2 $MMTCO_2e$ (20.3%) from 2020 to 2050 and total emissions (above- and below-ground biomass) was 14.00 $MMTCO_2e$ (0.46 /yr), with 11.4 from direct emissions and 2.6 from forgone sequestration. Compared to the Counterfactual (no development) scenario, the Recent Trends results in a loss of 19.81 $MMTCO_2e$, and a reduction in sequestration of 17.22% between 2020-2050.

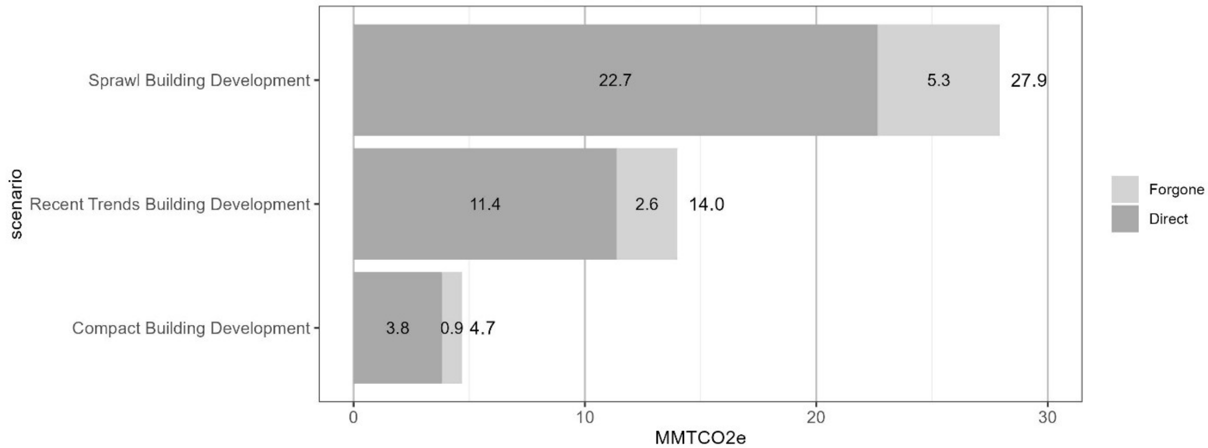

Figure 24. *Cumulative emissions from building development from 2020 to 2050 across Building Focus Scenarios, including direct emissions (dark gray) and forgone forest sequestration (i.e., carbon that would have been sequestered but for the deforestation caused by new greenfield building development; light gray).*

We also developed Sprawl and Compact scenarios to estimate the effect of either higher or lower building development rates in the future. The Sprawl scenario doubles the recent trends rate of greenfield building development resulting in a 15.9% gain in developed area by 2050. The Compact scenario reduces the recent trends rate of development to one third resulting in 2.6% growth in developed area by 2050. In the Sprawl scenario, live carbon increases by 82.1 MMTCO_2e (17.5%) from 2020 to 2050 and total emissions (above- and below-ground biomass) was 27.9 MMTCO_2e (0.93 MMTCO_2e/yr), with 22.7 from direct emissions and 5.3 from forgone sequestration. In the Compact scenario, stored carbon increases by 104.1 MMTCO_2e (22.2%) from 2020 to 2050 and total emissions (above- and below-ground biomass) was 4.7 MMTCO_2e (0.16 MMTCO_2e/yr), with 3.8 from direct emissions and 0.9 from forgone sequestration. Compared to the Counterfactual (no development) scenario, the Sprawl scenario results in a loss of 33.00 MMTCO_2e while the Compact scenario results in a loss of 10.98 MMTCO_2e. A change from recent trends to sprawl building development represents a 13.85% (13.19 MMTCO_2e or 0.44 MMTCO_2e/yr) reduction in sequestration between 2020-2050 while a change from recent trends to compact building development would result in a 9.27% (8.83 MMTCO_2e or 0.29 MMTCO_2e/yr) gain in sequestration between 2020-2050. The Sprawl and Compact Building Focus Scenarios are both components of the Integrated Scenarios described previously.

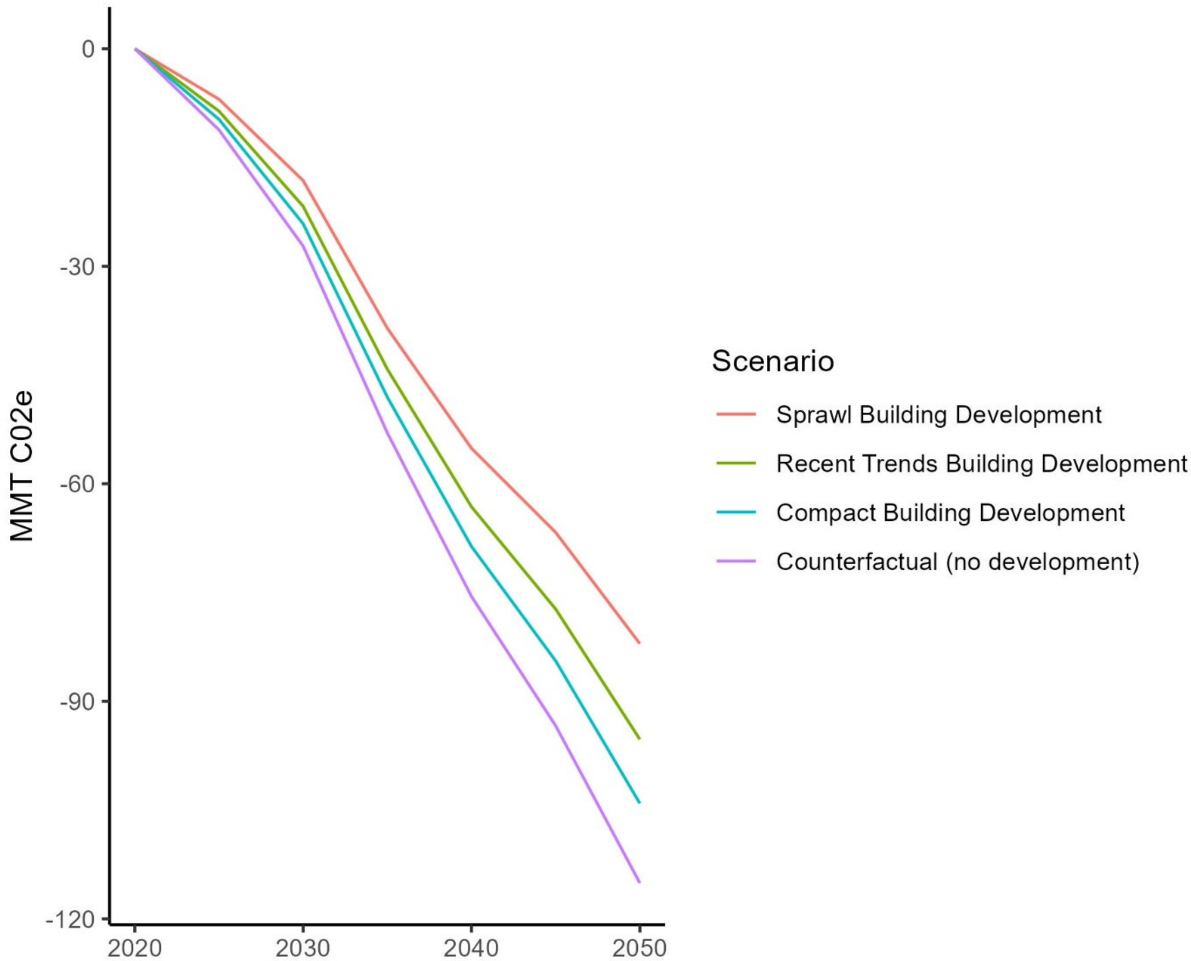

Figure 25. *Accumulation of carbon from 2020 to 2050 in live carbon pools (above- and below-ground biomass) in the Building Development Focus Scenarios. Negative values indicate cumulative carbon removal from the atmosphere (i.e. cumulative negative emissions). These scenarios include recent trends harvest, low ecological disturbance, and different quantities of land conversion from building development (see Table 7). The Counterfactual (no development) scenario, includes recent trends harvest and low levels of ecological disturbance.*

Solar Development Results

We assessed five alternative greenfield solar development scenarios and estimated the impact on terrestrial carbon by comparing each scenario to a Counterfactual (no development) scenario with no new development for buildings or solar. The five Solar Focus Scenarios differ in the proportion of solar development occurring on greenfield sites (rather than on already developed land), the land use intensity (LUI) of solar development (ha/MW), and in the strictness of greenfield siting criteria (Table 8). All the scenarios (except for the Counterfactual) achieve Massachusetts' anticipated 2050 solar capacity needs of $27GW_{AC}$, and all scenarios include the same forest ecosystem dynamics and recent trends-based gap-scale disturbances and harvesting. The spatial distribution of solar development under each scenario is shown in Figures 26 and 27, and emissions and live carbon accumulation are shown in Figures 28 and 29.

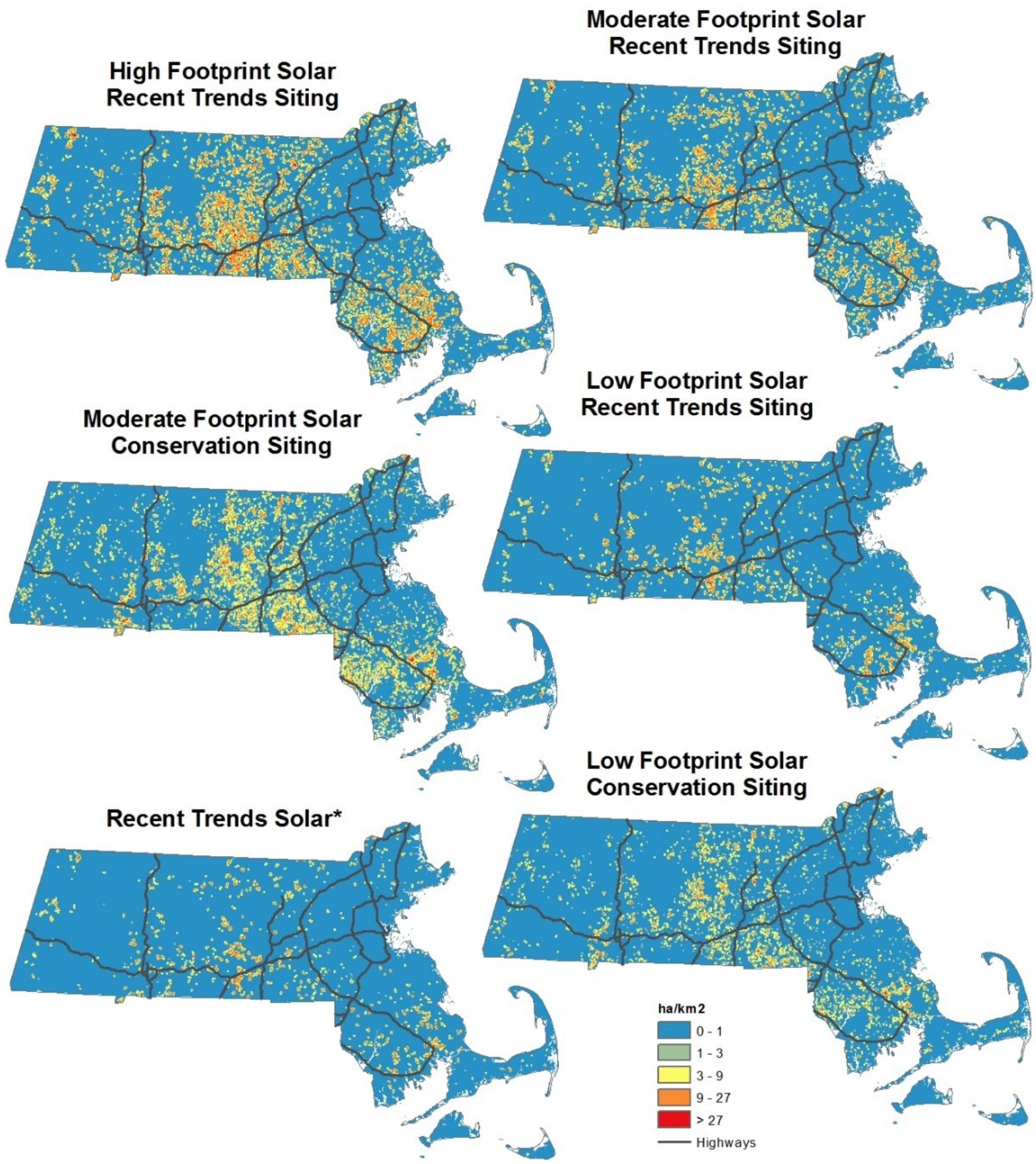

Figure 26. *Spatial distribution of new greenfield solar development. *Note that unlike the other scenarios, Recent Trends Solar continues building at the observed recent rate of new greenfield development and thus does not hit the state's anticipated need for 27 GW of capacity by 2050. The High Footprint Recent Trends Siting and Low Footprint Conservation Siting are used in the Integrated Scenarios while the other distributions are used in the Focus Scenarios. Data has been smoothed for visualization using a 10km moving window showing hectares of new greenfield solar per square kilometer.*

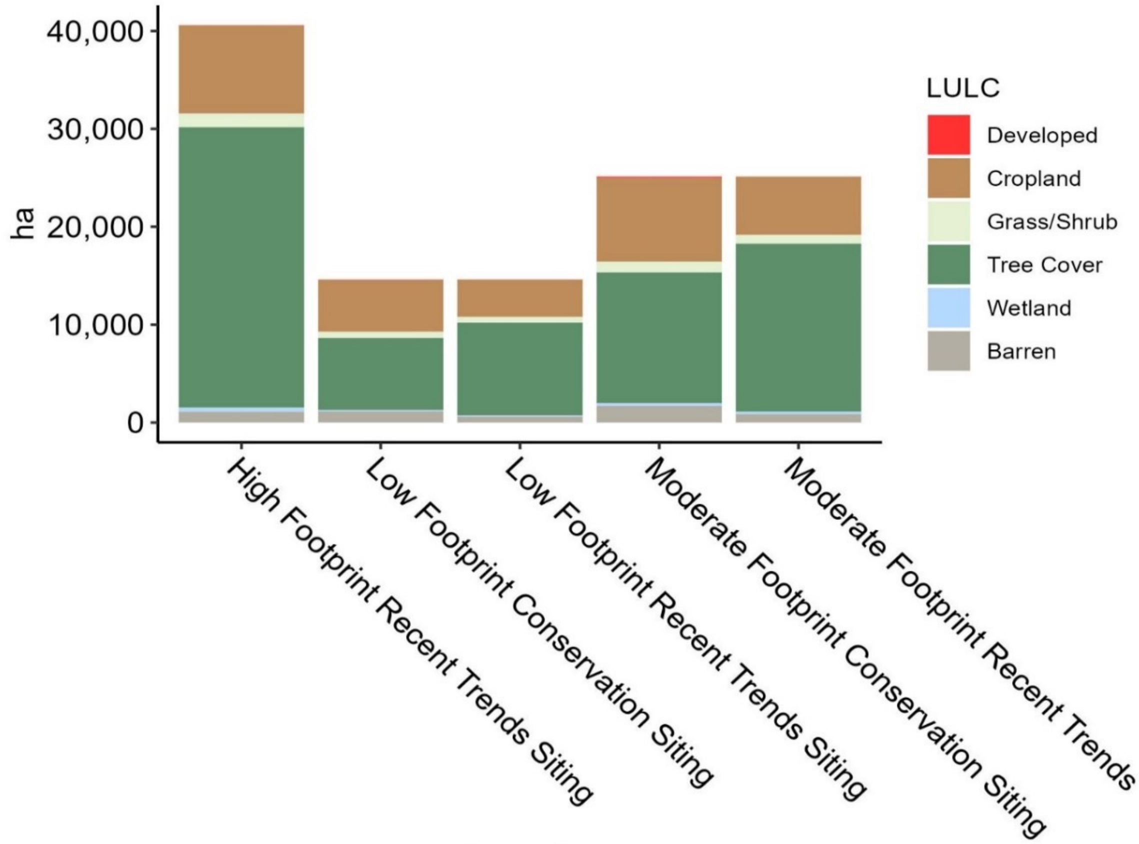

Figure 27. *Area of new greenfield solar development by 2020 land cover class that was converted between 2020 to 2050. The Integrated Scenarios use the High Footprint Recent Trends Siting and Low Footprint Conservation Siting scenarios. A small area of conversion from the Developed class results from land undergoing multiple transition types over time (e.g. Developed to Barren to Solar). Wetland conversions depicted here are based on LCMAP land cover data, however, MassDEP-mapped wetlands were excluded from solar development.*

The High Footprint and Recent Trends Siting scenario uses a LUI factor of 2.75 ha/MW, assumes that 66% of new solar capacity is built on greenfield sites, and uses siting criteria reflecting recent trends (see Table 9). In this scenario, total emissions from solar development (above- and below-ground biomass) were 13.5 MMTCO$_2$e (0.45 MMTCO$_2$e /yr), with 10.9 from direct emissions and 2.7 from forgone sequestration. Live carbon increased by 85.4 MMTCO$_2$e (18.2%) from 2020 to 2050. Compared to the Recent Trends scenario (which does not hit the 27 GW$_{AC}$ anticipated need), this scenario resulted in a loss of 9.89 MMTCO$_2$e, representing a 10.38% decrease in sequestration between 2020-2050.

The Low Footprint and Recent Trends Siting scenario uses a LUI factor of 1.46 ha/MW, assumes a linear decrease to 33% of total capacity being greenfield development, and uses siting criteria reflecting recent trends (see Table 9). In this scenario, total emissions from solar (above- and below-ground biomass) were 4.5 MMTCO$_2$e (0.15 MMTCO$_2$e/yr), with 3.6 from direct emissions and 0.9 from forgone sequestration. Live carbon increased by 93.8 MMTCO$_2$e (20.0%) from 2020 to 2050. Compared to the Recent Trends scenario (which does not hit the 27 GW$_{AC}$ anticipated need), this scenario results in a loss of 1.49 MMTCO$_2$e, representing a 1.56% decrease in sequestration between 2020-2050.

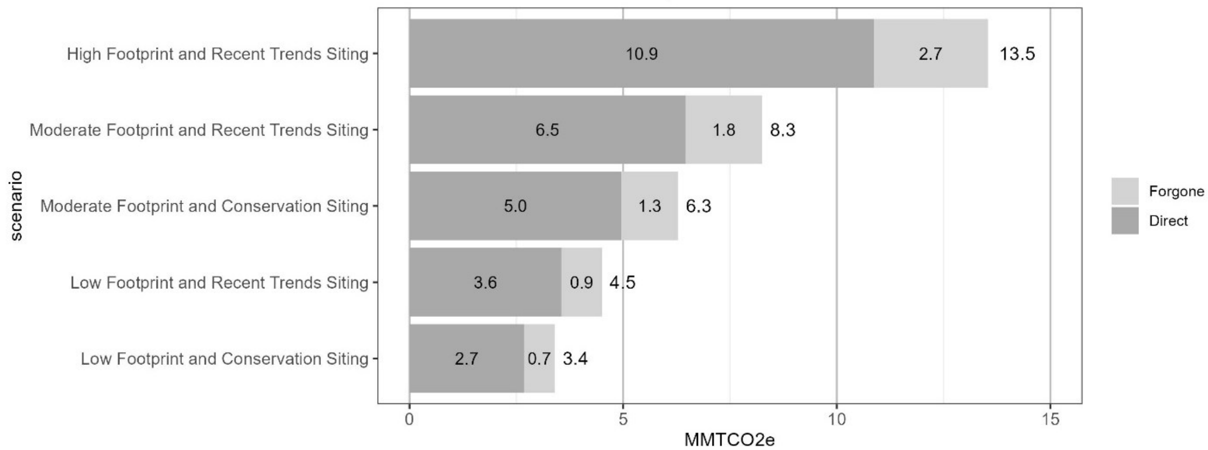

Figure 28. *Cumulative emissions from solar development from 2020 to 2050 across the Solar Focus Scenarios, including direct emissions (dark gray) and foregone forest sequestration (i.e., carbon that would have been sequestered but for the deforestation caused by new greenfield solar development (light gray).*

The Low Footprint and Conservation Siting scenario uses a LUI factor of 1.46 ha/MW, assumes a linear decrease to 33% of total capacity being green field development, and contains strict siting criteria (see Table 9). In this scenario, total emissions from solar (above- and below-ground biomass) were 3.4 $MMTCO_2e$ (0.11 $MMTCO_2e$/yr), with 2.7 from direct emissions and 0.7 from forgone sequestration. Live carbon increased by 94.6 $MMTCO_2e$ (20.2%) from 2020 to 2050. Compared to the Recent Trends scenario (which does not hit the 27 GW_{AC} anticipated need), this scenario resulted in a loss of 0.61 $MMTCO_2e$, representing a 0.65% decrease in sequestration between 2020-2050.

The Moderate Footprint and Recent Trends Siting scenario uses a 'improving' LUI factor that decreases linearly from 2.75 ha/MW in 2020 to 1.46 ha/MW by 2050, assumes a constant 50% of total capacity will be greenfield development, and siting criteria reflecting recent trends (see Table 9). In this scenario, total emissions from solar (above- and below-ground biomass) were 8.3 $MMTCO_2e$ (0.28 $MMTCO_2e$/yr), with 6.5 from direct emissions and 1.8 from forgone sequestration. Live carbon increased by 90.3 $MMTCO_2e$ (19.2%) from 2020 to 2050. Compared to the Recent Trends scenario (which does not hit the 27 GW_{AC} anticipated need), this scenario resulted in a loss of 4.90 $MMTCO_2e$, representing a 5.14% decrease in sequestration between 2020-2050.

The Moderate Footprint and Conservation Siting scenario uses a 'improving' LUI factor that decreases linearly from 2.75 ha/MW in 2020 to 1.46 ha/MW by 2050, assumes a constant 50% of total capacity will be green field development, and contains limited siting criteria (see Table 9). In this scenario, total emissions from solar (above- and below-ground biomass) were 6.3 $MMTCO_2e$ (0.21 $MMTCO_2e$/yr), with 5.0 from direct emissions and 1.3 from forgone sequestration. Live carbon increased by 91.9 $MMTCO_2e$ (19.2%) from 2020 to 2050. Compared to the Recent Trends scenario (which does not hit the 27 GW_{AC} anticipated need), this scenario resulted in a loss of 3.33 $MMTCO_2e$, representing a 3.49% decrease in sequestration between 2020-2050.

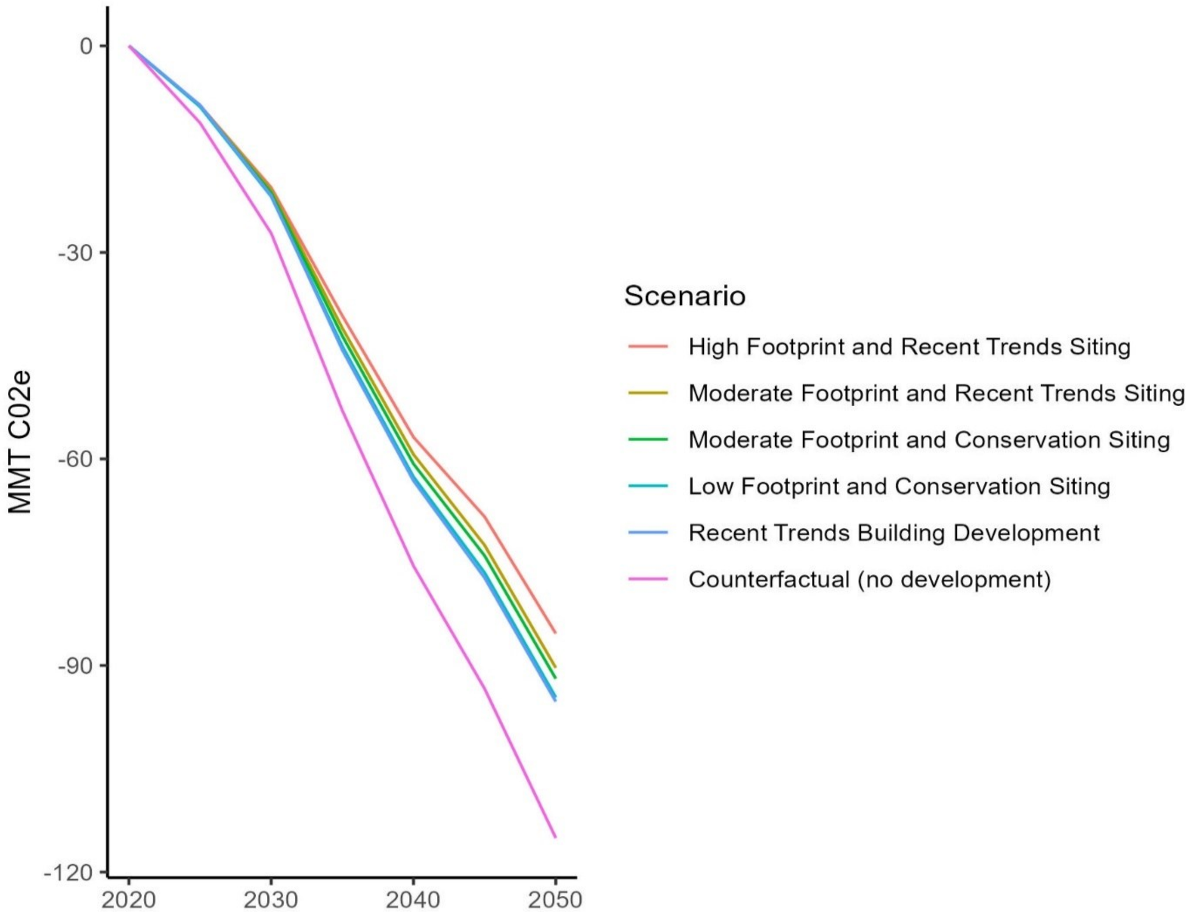

Figure 29. *Accumulation of carbon from 2020 to 2050 in live carbon pools (above- and below-ground biomass) in the Solar Development Focus Scenarios. Negative values indicate cumulative carbon removal from the atmosphere (i.e. cumulative negative emissions). These scenarios include recent trends harvest, low ecological disturbance, and different quantities of land conversion from solar development (see Table 8). The Counterfactual (no development) scenario includes recent trends harvest and low levels of ecological disturbance.*

Reforestation and Tree-Planting Results

We modeled four alternative reforestation and tree-planting scenarios, including a baseline scenario with reference period-based reforestation and urban tree planting rates, plus three scenarios with additional active reforestation and tree planting. The baseline scenario includes passive reforestation of 329 ha/year through 2050, resulting in -1.46 MMTCO$_2$e of carbon accumulation between 2020 and 2050 (Figure 30A), with rates reaching -0.09 MMTCO$_2$e/yr in 2050. The modest scenario includes active reforestation on an additional 263 ha/year, resulting in -1.17 MMTCO$_2$e of carbon accumulation by 2050 (-0.10 MMTCO$_2$e/yr in 2050), while the ambitious scenario includes 658 ha/year of active reforestation, resulting in –2.91 MMTCO$_2$e of carbon accumulation (-0.26 MMTCO$_2$e/yr in 2050), and the maximum scenario includes 1316 ha/year of active reforestation, resulting in -5.83 MMTCO$_2$e of carbon accumulation (-0.51 MMTCO$_2$e/yr in 2050; where negative values indicate removal of carbon from the atmosphere). While we did not simulate reforestation of additional land past 2050, we did model carbon accumulation on land reforested by 2050 out to 2100, with total accumulation at the end of the century ranging from -4.61 $MMTCO_2e$ for the modest scenario to -22.95 $MMTCO_2e$ for the maximum scenario (Figure 30A).

For urban tree planting, the baseline scenario adds 6,156 trees/year, while the modest scenario adds 61,672 trees/year, the ambitious scenario adds 154,183 trees/year, and maximum scenario adds 308,363 trees/year between 2020 and 2050. Each of these scenarios included variants with either typical levels of mortality or idealized levels of mortality (i.e. no mortality). Between 2020 and 2050, carbon accumulation from urban tree planting ranged from 0.08 $MMTCO_2e$ for the modest scenario with typical mortality (-0.007 $MMTCO_2e$/yr in 2050) to 0.59 $MMTCO_2e$ for the maximum possible with idealized mortality (-0.050 $MMTCO_2e$/yr in 2050). By 2100, carbon accumulation from urban trees planted during the 2020 to 2050 time period ranged from 0.71 $MMTCO_2e$ for the modest scenario with typical mortality (-0.018 $MMTCO_2e$/yr in 2100) to 6.30 $MMTCO_2e$ (-0.176 $MMTCO_2e$/yr in 2100) for the maximum possible with idealized mortality (Figure 30B).

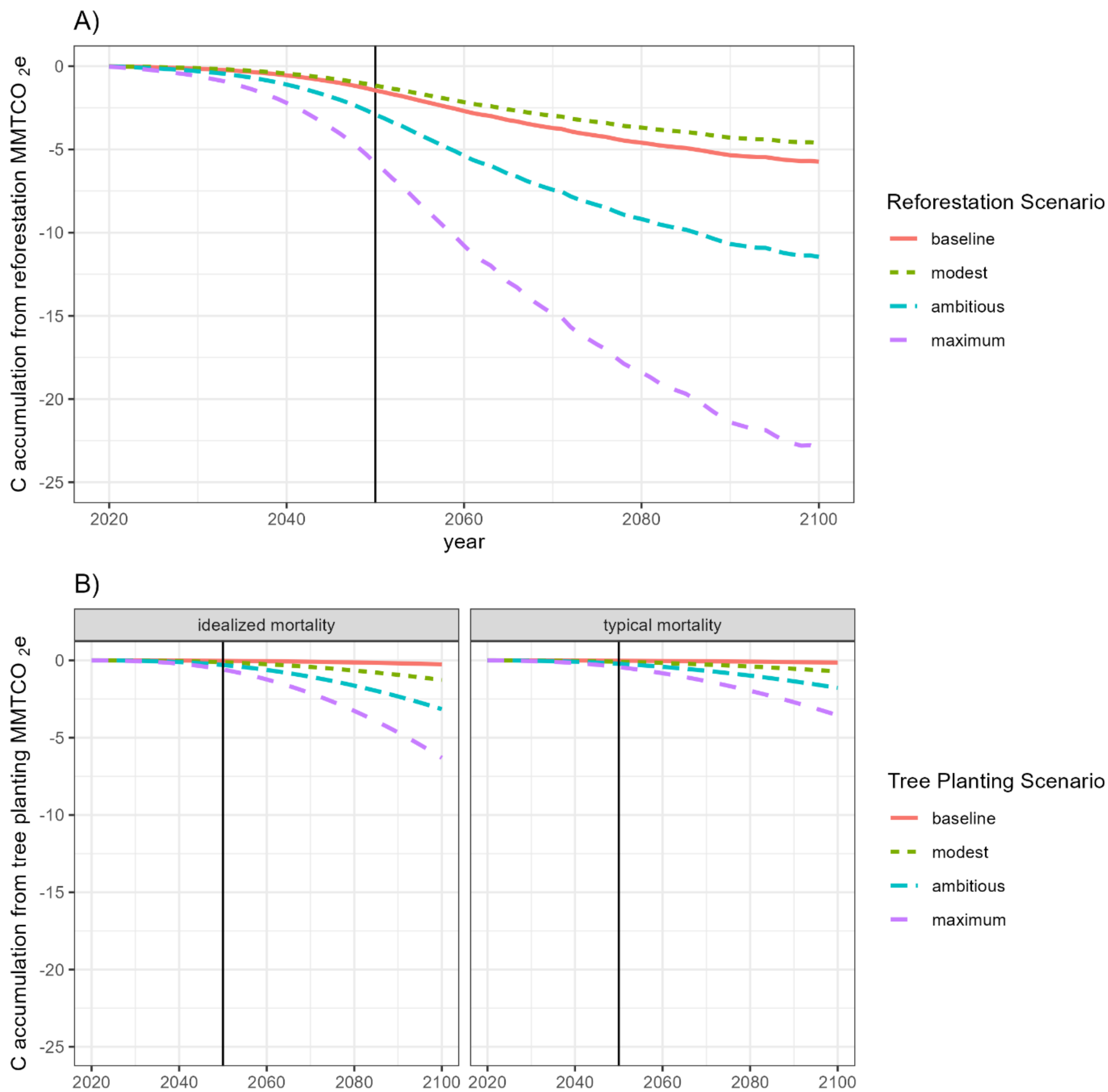

Figure 30. *Carbon accumulation (MMTCO2e) over time from reforestation (A) and urban tree planting (B) carbon, where negative values indicate removal of carbon from the atmosphere. Results reflect both baseline and additional, active reforestation and tree-planting efforts occurring between 2020 and 2050, with the carbon removal effects of these efforts shown to 2100. The black vertical line is 2050, the MA net zero compliance year.*

4.3 Forest Adaptive Capacity and Resiliency Results

Forest Structure Results

Figure 29 shows the proportion of the modeled forest landscape in each structural class. General patterns of aging of the forest are evident; and disturbance—harvest and modeled wind and pests/pathogens—have an effect on the distribution of structural classes. In general, the high disturbance scenarios have greater evenness of structural conditions over time as measured by Simpson's Diversity (Figure 30). This landscape-level perspective, however, masks important differences in the dynamics of the structural classes over time.

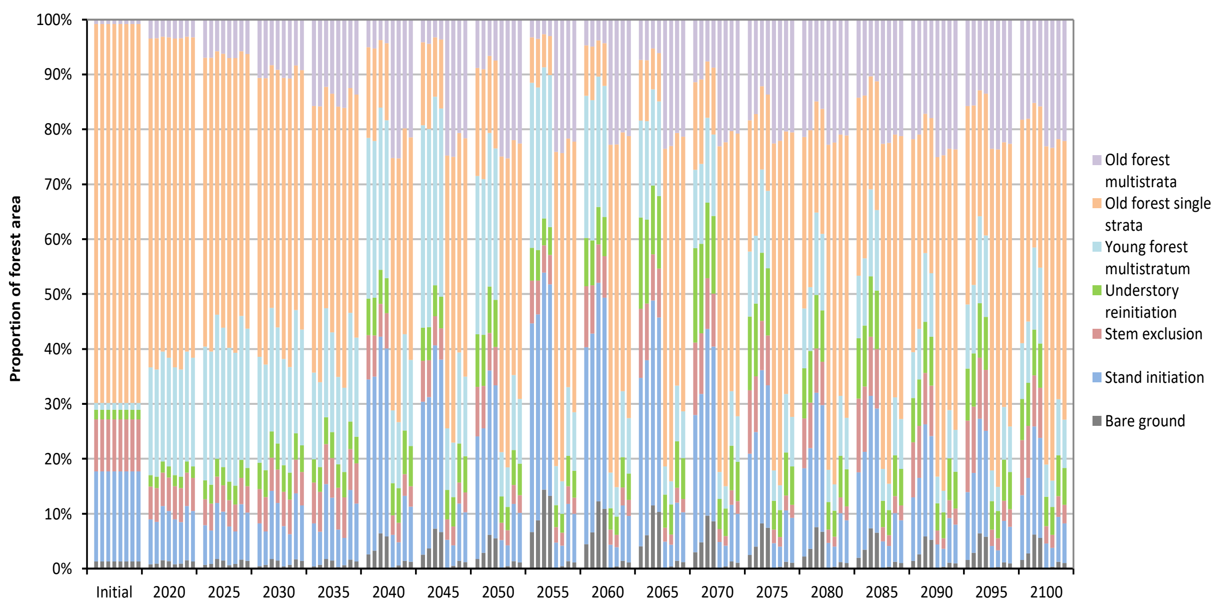

Figure 29. *Proportion of forest area in different structural classes, for each scenario and time step. Within each time step, scenarios are ordered from left to right as High Disturbance Recent Trends, High Disturbance Reserve Emphasis, High Disturbance Local Wood Emphasis, High Disturbance Combined Emphasis, Low Disturbance Recent Trends, Low Disturbance Reserve Emphasis, Low disturbance Local Wood Emphasis, and Low Disturbance Combined Emphasis.*

Comparing harvested and unharvested areas separately emphasizes the characteristics of each type of area and allows for better evaluation of the effects of silviculture. This is especially important since relatively little forest area is treated in the model for much of the temporal modeling horizon (Figure 31), and especially before severe disturbances are introduced. For example, across all the scenarios, well under half the area of Massachusetts' forests remains unharvested for at least two decades, until 2035 (high and low disturbance Local Wood Use

Emphasis scenarios). In some scenarios (high disturbance Recent Trends scenario, high and low disturbance Reserve Emphasis scenarios), less than half of the forested area is ever harvested by 2100.

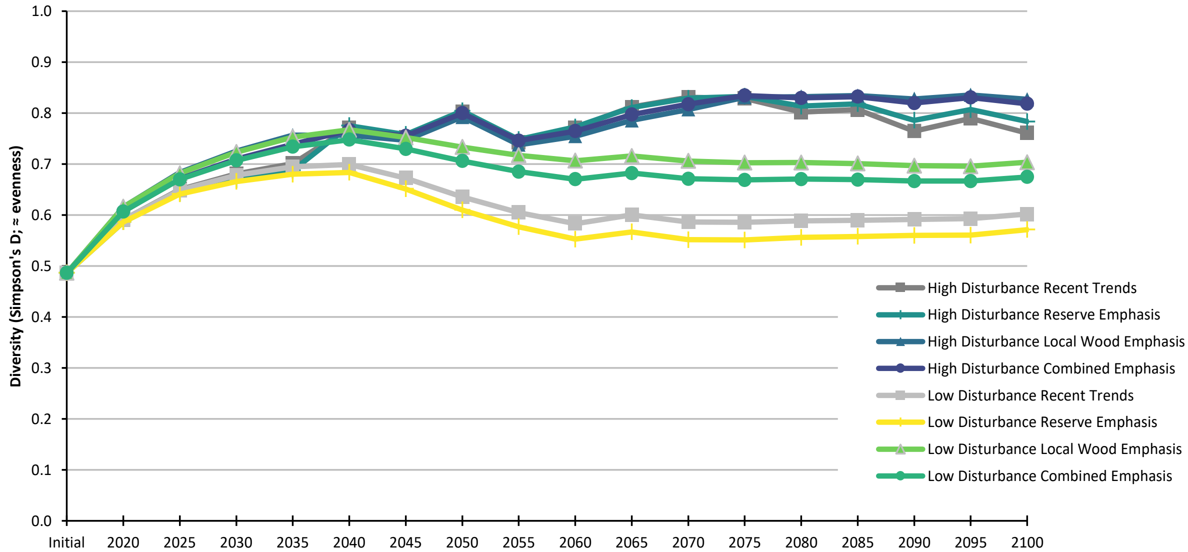

Figure 30. *Simpson's diversity index assessed for forest structural classes, for each scenario and time step.*

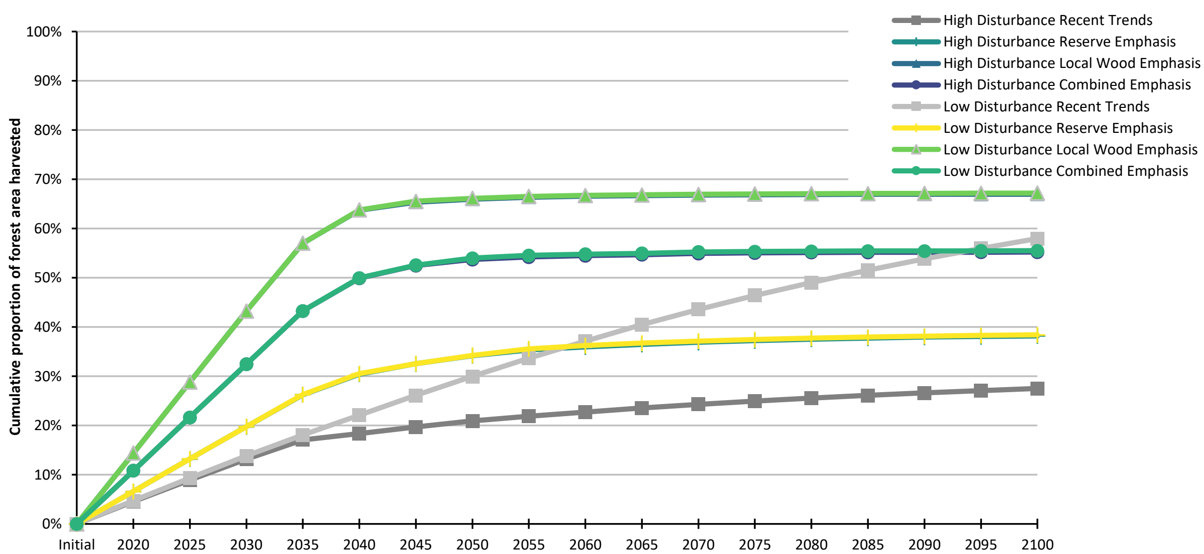

Figure 31. *Cumulative proportion of forest area harvested, by scenario and time step.*

When the proportion of forest in the different structural classes is analyzed separately on land that has been treated, and land that has not (Figure 32, small multiples), several patterns emerge. First, there is generally a more even distribution of structural classes over time, and more younger structural classes (bare ground, stand initiation) in areas that have had harvesting. The unharvested area tends to have a larger proportion in the old forest single-stratum class, and a slightly larger proportion in the old-forest multi-stratum class. In the high-disturbance scenarios, areas that had been harvested had a slightly greater proportion of forest area in the stand initiation structural class. This could be expected as the probability of disturbance across harvested and unharvested areas was unequal: priority was given to harvesting areas to that were more disturbance-prone. In addition, the harvesting modeled in this exercise was not adaptive, and could not be reallocated or adjusted in response to changing landscape conditions, as it could be in reality. The areas that have been treated have a more stable distribution of structural class proportions over time, experiencing less dramatic shifts in the area of different classes. The only exception to this was the old forest multistrata class, which, despite the harvested areas starting from a large deficit early in the modeling time period, was quite close in numeric measures of variability. Importantly, it shows that managed forests can, with deliberate silviculture, provide or emulate the full range of structural conditions, if not absolute ages – from complex late-successional to young forest – in proportions not significantly different from unmanaged areas. This reinforces the role of deliberately planned silviculture in creating continuity of conditions wildlife habitat and other ecosystem services to complement other landscape-scale land use decisions.

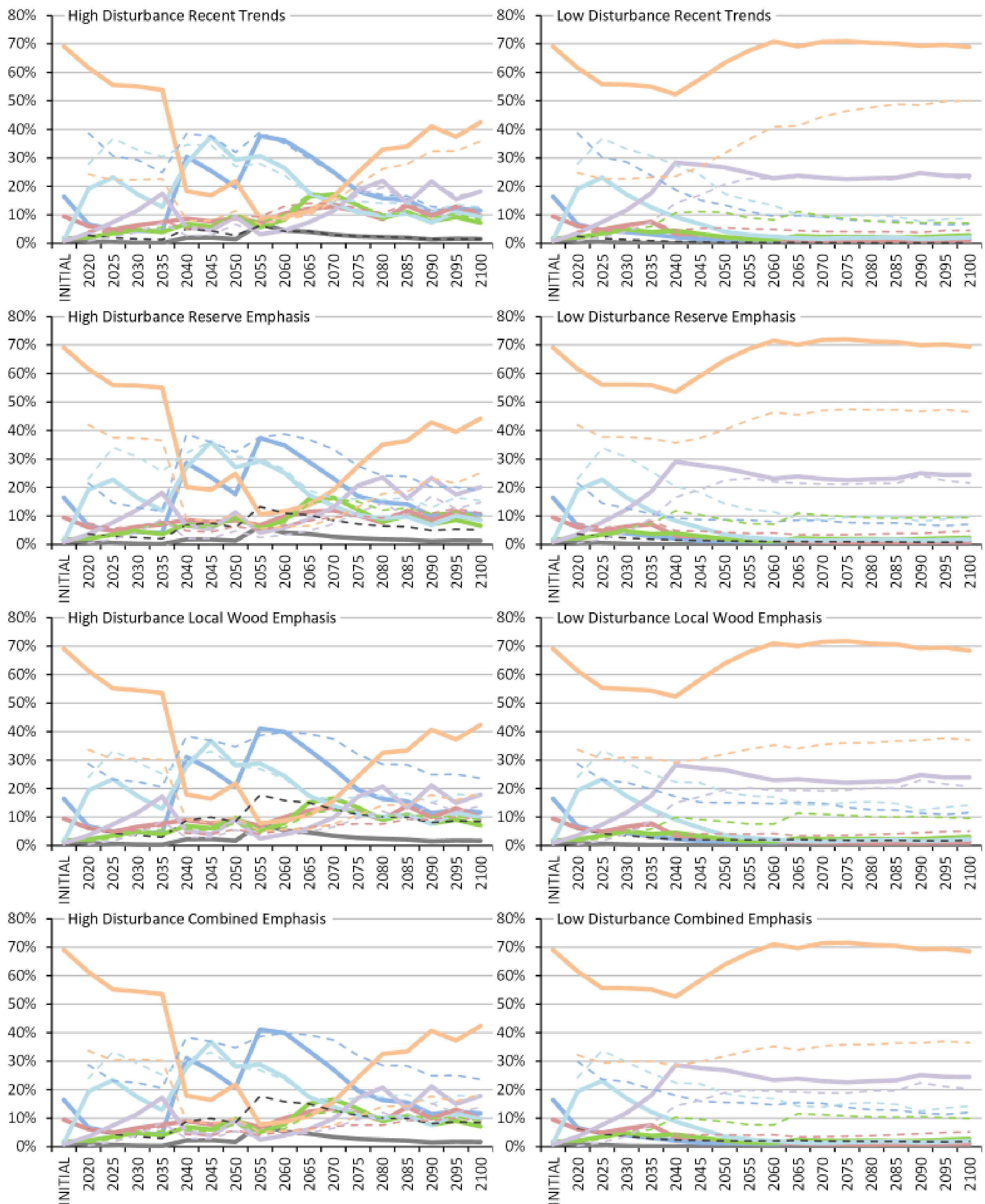

Figure 32. Proportion of forest area in different structural classes, for each scenario and time step.

Figure 33 shows the area of structurally young forest (two youngest structural conditions grouped together) and patch size composition over time. The scenarios with a greater emphasis on harvesting, and to a lesser extent CSF/COF, had a larger and more stable proportion of structurally young forest in larger contiguous patches over time. In the absence of significant disturbance, there is concentration into smaller patches with possible implications for habitat. This once again reinforces the balance between active and passive management; with a role for silviculture in ensuring continuity of conditions.

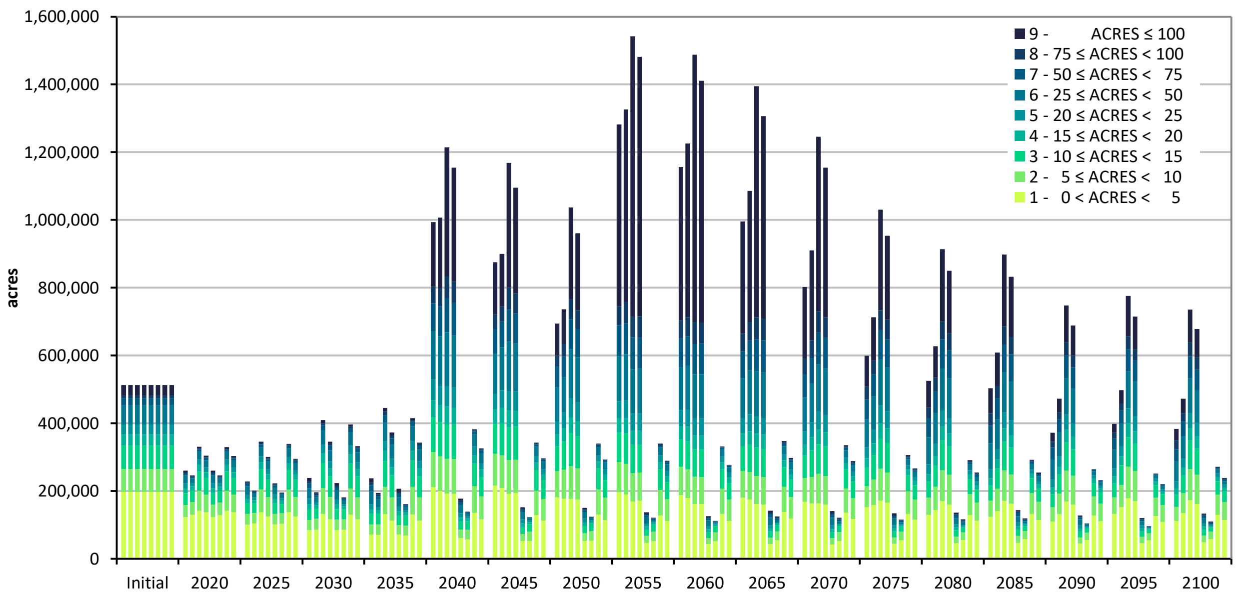

Figure 33. *Area of structurally (bare ground and stand initiation classes) young forest, expressed as the total height of each bar; and proportion in patches of different contiguous area (different colored sections within each bar), by time step and scenario. Within each time step, scenarios are ordered from left to right as High Disturbance Recent Trends, High Disturbance Reserve Emphasis, High Disturbance Local Wood Emphasis, High Disturbance Combined Emphasis, Low Disturbance Recent Trends, Low Disturbance Reserve Emphasis, Low disturbance Local Wood Emphasis, and Low Disturbance Combined Emphasis.*

Forest Composition Results

Figure 34 shows the proportion of above ground live tree biomass in each management priority category, across all age classes, for each scenario and time step (see Appendix VI, Table A7 of management priority rating for each modeled species). Generally, all scenarios showed relatively constant or slight increases in the proportion of biomass in high-priority and medium-priority species combined. The proportion of biomass in high-priority species increased slightly, while the proportion of biomass in medium-priority species decreased slightly. Scenarios with greater rates of disturbances showed stronger early increases in the proportion of biomass in high-priority species; while scenarios with an emphasis on local wood production using CSF/COF practices showed a greater increase in the proportion of biomass in high- and medium-priority species within disturbance regimes.

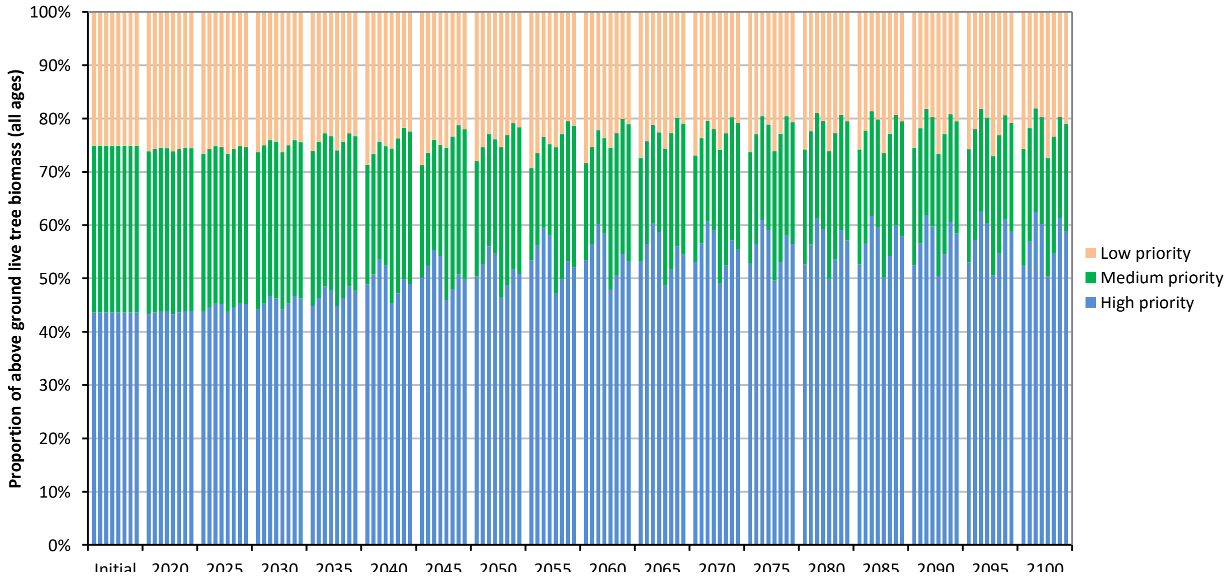

Figure 34. *Proportion of above ground live tree biomass of all cohorts, in modeled species, by management priority, time step, and scenario. Scenarios are, from left to right within the eight bars of each time step, High Disturbance Recent Trends, High Disturbance Reserve Emphasis, High Disturbance Local Wood Emphasis, High Disturbance Combined Emphasis, Low Disturbance Recent Trends, Low Disturbance Reserve Emphasis, Low Disturbance Local Wood Emphasis, and Low Disturbance Combined Emphasis.*

Within the youngest cohort (0-10 years old, e.g., seedlings), all scenarios saw a slight decline in the proportion of biomass in high- and medium-priority species. High-disturbance scenarios showed smaller declines; and the scenarios employing recent trends practices showed small declines within disturbance regimes. Roughly similar results were evident for the next-oldest cohort (10-25 years old, e.g., saplings). However, results for the 25-50 year old cohort (e.g., poletimber, Figure 35) demonstrated strong gains, resulting from the persistent tending of regeneration and cultural work in the silvicultural prescriptions. Across all scenarios, results show a decline until 2040 in the proportion of high- and middle-priority species; followed by strong gains for the rest of the century. The scenarios with a high disturbance regime generally show greater biomass in high- and moderate-priority species; and the scenarios emphasizing local wood production show consistently greater biomass than other scenarios.

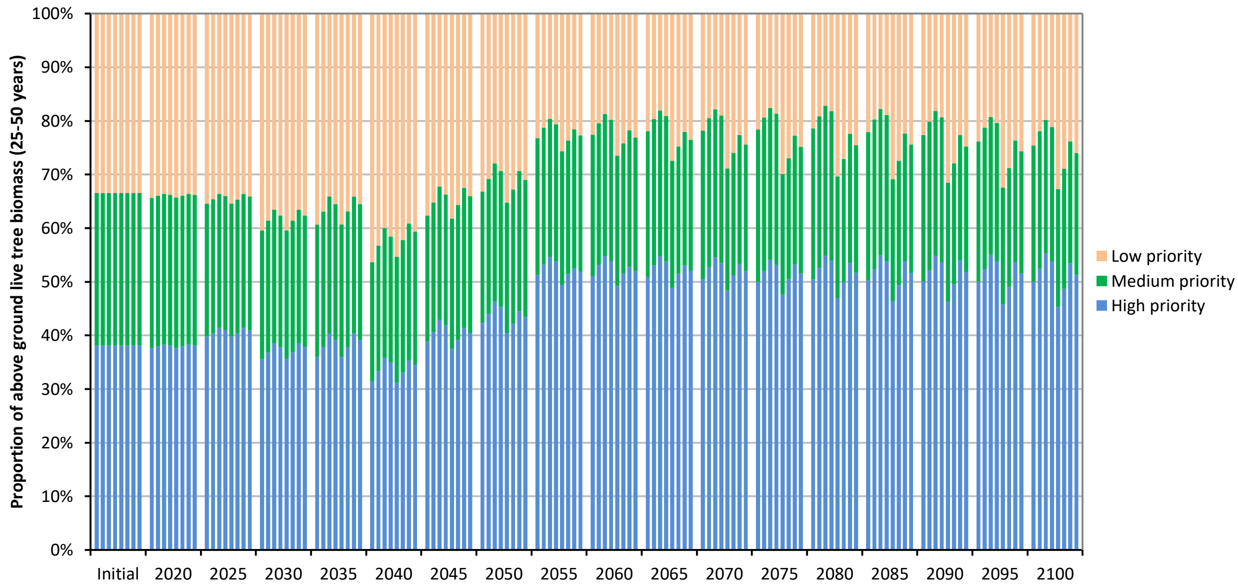

Figure 35. *Proportion of above ground live tree biomass of 25-50 year old cohort, in modeled species, by management priority, time step, and scenario. Scenarios are, from left to right within the eight bars of each time step, High Disturbance Recent Trends, High Disturbance Reserve Emphasis, High Disturbance Local Wood Emphasis, High Disturbance Combined Emphasis, Low Disturbance Recent Trends, Low Disturbance Reserve Emphasis, Low Disturbance Local Wood Emphasis, and Low Disturbance Combined Emphasis.*

Case Studies of Silvicultural Outcomes

A broad, statewide view of forest composition masks considerable variability in results, as well as the contextual and long-term nature of sound silviculture. Also, as disturbances are occurring throughout the modeled time period, the responses of areas that do not have a history of silvicultural treatment are being conflated with those that do; and the area treated early in the model is relatively small compared to the area that is not treated. Exploring the effects of silviculture through a series of case studies shows that silviculture can have a strong effect on ecosystem health and resilience outcomes for specific natural communities commonly found in different regions of the Commonwealth. Results are detailed in Appendix VIII.

In summary, the modeled silvicultural treatments and CSF/COF successfully regenerated, recruited, and perpetuated keystone species that are central to the structure and function of natural communities investigated in the case studies (pitch pine in eastern Massachusetts, oak-hickory in central Massachusetts, and northern hardwoods and spruce-fir communities in western Massachusetts). For example, while management practices specific to pine barrens management were not simulated, the silviculture that was modeled helped maintain pitch pine in pitch pine communities – a critical natural community type in eastern Massachusetts – in both younger and older cohorts relative to areas that were not treated. This reinforces the role of silviculture in maintaining the resilience of this community's structure and function.

The modeled silviculture also resulted in more successful regeneration of keystone tree species, relative to untreated areas, in other communities, such as the oak-hickory community in central Massachusetts and the beech-birch-maple and spruce-fir communities in western Massachusetts. Treated areas, and modeled CSF/COF in particular, resulted in substantial regeneration of the hickory species included in the study, while limiting the abundance of ecologically challenging species such as beech, relative to untreated areas. They also help perpetuate the spruce-fir community in older age classes relative to untreated areas.

Tree species richness and diversity are also important measures of community resilience. Treated areas, and modeled CSF in particular, help improve regeneration diversity (richness and evenness) in the beech-birch-maple community relative to untreated areas. There is a decline in species diversity over time in the oak hickory community as measured by Simpson's D (a measure of how evenly or concentrated members of a population are within different classes or domains), but the decline is less in the absence of too much and too little disturbance. This indicates that silviculture can help improve species diversity.

The number of different age classes represented (richness) is another important indicator of resilience. Trees are susceptible to different stressors and damaging agents at different points in their life; having trees present from an appropriate number of different ages can help a site be more resilient, re-occupy vacated growing space more rapidly, and stabilize ecosystem service provision. Treated areas, and modeled CSF/COF, accelerate age class diversification for the oak-hickory, northern hardwoods, and spruce-fir communities.

In addition to enhancing ecosystem health and resilience, the modeled recent trend silviculture and CSF/COF silviculture was found to mitigate the loss of live tree carbon from hurricanes. In scenarios with hurricanes, areas that were harvested early in the modeling period lost 58.5%-72.5% less carbon on a per-acre basis to hurricane damage than areas that were not harvested. The most severe losses were from the first modeled hurricanes, in which the scenario employing recent trends silviculture, and the scenario emphasizing CSF/COF silviculture with local wood emphasis, reduced those early losses the greatest (60.1% and 41.0%, respectively). Even after the first modeled hurricane, the amplitude of damage from subsequent hurricanes is far less (61.4%-137.8%).

Silvicultural treatments also moderated losses of live tree carbon from non-hurricane disturbances and hurricanes with strength less than EF2. Areas treated early with the modeled recent trends silviculture still showed reduced mean losses from non-hurricane disturbances (6.9% less in the high-disturbance scenario, and 7.4% less in the low disturbance scenario), and a smaller range of losses. Areas treated with CSF/COF silviculture saw larger reduction in mean live carbon losses (19.4% less in the high-disturbance scenario, and 7.4% less than the low disturbance scenario), and a smaller range of losses from time step to time step (i.e., more stability) on the order of 43.0%-70.0% less range than untreated areas in the high disturbance scenarios, and 24.0%-39.7% less range than untreated areas in the low disturbance scenarios. The scenarios with the greatest reductions in mean losses and increases in stability were the local wood emphasis and combined emphasis scenarios.

5. Discussion and Conclusions

5.1 Forest Disturbance Risks

Accounting for the risk of impermanence—or the risk that sequestered carbon will be re-released into the atmosphere—is a major challenge for policymakers wishing to use terrestrial carbon sequestration to "offset" fossil fuel emissions. Estimating whether (or how much) sequestered carbon is permanently removed from the atmosphere requires an understanding of the role of future disturbances, such as hurricanes, insects, and droughts, for carbon dynamics.[8] Because major disturbance events are rare, stochastic, and often highly impactful, estimating the permanence of offsets is a subject of considerable debate and research (e.g., Balmford et al 2023; Groom and Venmans 2023). Furthermore, risks to the permanence of carbon in the land sector are projected to increase due to climate change, and, therefore, estimates based on past observations will underestimate the true risk that forests will experience under a warming climate (Conradi et al 2024).

Here we examined the potential role for invasive forest insects and hurricanes to influence the permanence of forest carbon stores in Massachusetts. For insects, we specifically considered the impacts of EAB and HWA, which are extirpating ash and hemlock trees from the state. We find that these insects will have minor impacts on landscape scale carbon. There are three primary reasons for this. First, when a tree dies due to insect infestation, it stops taking up carbon and slowly re-releases its carbon to the atmosphere via decomposition. Complete decomposition of adult trees takes decades (Harmon et al 2020). Second, these insects kill their hosts trees over a protracted timespan—particularly HWA, which can take decades to kill a hemlock (Orwig et al 2012). As the insects slowly kill their host,[9] new tree species establish in the understory using the newly available light and growing space. The rate of carbon sequestration by the newly established cohorts is often slightly higher than the pre-infestation rate due to age- and species-related difference in productivity. New growth and sequestration then substitute the slow loss of ash and hemlock carbon through decomposition. Third, ash and hemlock constitute a minor fraction of total forest carbon (four and six percent in 2020, respectively); so, their loss is readily compensated for by other species.

While we find that the loss of these specific host trees is unlikely to have a significant impact on regional carbon fluxes, there are still many reasons to be concerned about these and other forest insects and diseases. Most significantly, perhaps, is the impact that their loss will have on regional biodiversity and habitat. Hemlock is a foundation species (Ellison et al 2008) with many other species and ecosystem processes dependent on it. In addition, these species have significant cultural value. Ash trees, for example, are especially important to many Indigenous communities, as they are a primary material for basket making and other goods (D'Amato et al 2023). Also, in the context of carbon fluxes, it is just a matter of time before a generalist invasive insect or an insect whose host trees are more abundant (like *Acer*) becomes established. When this occurs, the ecosystem may not be able to compensate for the greater or more rapid loss of vegetation.

We also simulated the impact of hurricanes. Despite the period of relative quiescence over the past three decades, hurricanes are a dominant disturbance agent in New England (Boose et al

[8] California's regulatory markets use a standard convention that concludes that carbon kept out of the atmosphere for >100-years is considered permanent.

[9] In our modeling framework, this occurs via depletion of non-structural carbon reserves, which effectively starves the tree to death

2001). There were ten significant hurricanes in New England during the 20th century, the most impactful being the Great New England Hurricane of 1938, which downed more than 70% of the trees in central Massachusetts (Foster and Boose 1992). While there is significant uncertainty about how climate change might affect the frequency of future hurricanes, warming ocean temperatures are widely expected to increase hurricane severity (i.e., wind speeds are expected to increase by 6-16%; Bender et al 2010). Because we cannot predict the timing or storm track of future hurricanes, we used the simplifying assumption that frequency and location of storms in the 21st century would match what was observed in the 20th. To account for expected increases in severity, we increased windspeeds by eight percent above what was observed and modeled their impact on forests based on the age and species of trees (see Tumber Davila et al. 2024 for methodological details of our hurricane modeling).

Our results show that hurricanes have the potential to reshape regional forest carbon fluxes, and that the timing of future hurricanes could have significant impacts on the Commonwealth's policy goals. For example, in the Recent Trends with High Disturbance scenario, we simulate a major hurricane in 2038, which abruptly flips the net landscape carbon flux from a sink of approximately -7 $MMTCO_2e$/yr in the years before the hurricane to source of +4 $MMTCO_2e$/yr, on average, during the five years after (Figure 18). In 2050, when the Commonwealth is legislatively committed to achieving Net Zero emissions, the land sector has just returned to being a net sink, with a net flux of only -1 $MMTCO_2e$/yr. An alternative future may see limited effects of hurricanes on mid-century forest carbon fluxes (e.g. the Low Disturbance scenarios, Figure. 18), or even an enhanced sink (e.g. if a hurricane occurred earlier), however, the ability for a single high severity weather event to flip the land sector from a sink to a source of atmospheric carbon highlights the broader permanence risk of terrestrial carbon.[10] While the future cannot be predicted, managing for different disturbance risks will continue to be important, especially with climate change uncertainties.

5.2 Land Cover Change

Here we examined a wide range of potential land use and land cover scenarios, including drivers and potential futures not considered in the original LSR. Unlike natural disturbances and timber harvesting, forest loss due to building and solar development is effectively permanent. This means that not only are the standing stocks of forest carbon emitted, but all future potential for forest sequestration is forgone too. Typically, for building development, cleared forests are chipped on-site, effectively emitting the aboveground carbon back to the atmosphere over just a few years. Less is known about the fate of cleared forests for greenfield solar. We examined both direct emissions and forgone sequestration across a range of building and solar development futures. Fluxes from direct emissions vary widely depending on the scenario, but forgone sequestration can increase the total by 23% to 50% by 2050 and would increase further over time. For these reasons, among the drivers affecting terrestrial carbon, deforestation presents the most intensive and permanent risk.

For building development, we simulated a six-fold difference in development rates and affected area between the Sprawl and Compact scenarios. This resulted in a similarly wide range of associated emissions, spanning 4.4 (0.15 $MMTCO_2e$/yr) to 27.9 $MMTCO_2e$ (0.93 $MMTCO_2e$/yr)

[10] It is worth noting that while the risks from disturbances on terrestrial carbon are real and important to understand, all economic sectors face analogous risks from disturbances, yet outside of the Land Sector they are rarely accounted for in climate mitigation planning—e.g., what are carbon emissions are associated with rebuilding energy, transportation, and building infrastructure after a major hurricane?

emissions by 2050. Given Massachusetts' substantial need for additional housing and other forms of building development (EEA 2022), there may be opportunities to limit the amount of this growth occurring on greenfield sites and thereby limit associated forest loss and emissions.

As with building development, our analysis of the potential emissions from future solar development emphasizes the risks and opportunities around solar land use. We estimate emissions under the Low Footprint with Conservation Siting scenario (3.4 $MMTCO_2e$ or 0.1 $MMTCO_2e$/yr) would be one quarter of the emissions under the High Footprint with Recent Trends Siting (13.5 $MMTCO_2e$ or 0.5 $MMTCO_2e$/yr), despite both scenarios achieving the state's anticipated need for 27 GW of solar production by 2050.[11] With the state just at the beginning of the required energy transition – solar generating capacity in Massachusetts was around 3 GW in 2020 (EEA 2022) – there may be opportunities to set policies and incentives that help limit the impacts to the lower end of that range. Solar development trends, incentives, and siting patterns in the past few years may already be resulting in less greenfield development than during the 2010 to 2020 reference period, thus curtailing impacts on forests and other natural and working lands.

Several factors could lead to higher or lower deforestation-driven emissions from building or solar development than those estimated here. On the one hand, this study indicates that emissions from forest conversion can be partially mitigated if wood from cleared sites is utilized in durable wood products (Table 16; note that the ongoing sequestration capacity of forests would still be lost). On the other hand, additional emissions from soil carbon can be expected from development on forests and other natural and working lands (discussed further in section 5.4).

The coordinated land cover change scenarios include both passive (or background) reforestation and active reforestation. For context, sequestration resulting from ambitious reforestation and tree planting along with background reforestation would "offset" the equivalent of 40% percent of the direct emissions associated with forest clearing for new buildings in a Recent Trends scenario (Figures 16 and 24). This likely is an optimistic projection, as active reforestation may occur in areas where passive reforestation would have occurred, and planting trees and reforesting tens of thousands of acres of open space is likely to face social and economic challenges, given competing land uses. The reforestation benefits estimated here should thus be considered as an upper bound on reforestations' mitigation potential.

5.3 Forest Management and Wood Utilization

Compared to its neighboring states to the north, Massachusetts has a very small forestry economy and harvests a small fraction of the wood it grows. Indeed, despite being ~57% forested, Massachusetts produces the equivalent of just 5% of lumber and 6% of the pulp it consumes (Littlefield et al 2024). Nonetheless, commercial timber harvesting contributes to land sector carbon emissions, releasing approximately 1.07 $MMTCO_2e$/yr between 2020-2050 in our Recent Trends Scenario (for reference, Massachusetts' gross GHG emission outside the land sector were 67 $MMTCO_2e$ in 2021, with transportation alone accounting for 26 $MMTCO_2e$ (MassDEP 2024)). While the land sector does produce emissions, it also removes atmospheric carbon at rates which can be altered through different land use practices. Whether the

[11] This does not account for the GHG emissions reductions that increased solar power generating capacity makes possible by reducing reliance on fossil fuel-based power generation, which is outside the scope of this study, but is explored elsewhere (e.g. https://harvard-forest.shinyapps.io/carbon-calculator/).

Massachusetts' forests should be utilized to help meet its in-state consumption or if wood should be imported from forests out of state is a subject of much debate and on which experts and stakeholders disagree (e.g., see the Commonwealth's Forests as a Climate Solutions initiative (EEA 2024)). A separate but related debate is whether harvest practices can be adapted to enhance carbon stocks and future sequestration. We examined scenarios that can inform both debates.

With regard to the impacts of meeting a greater proportion of the state's wood demand from Massachusetts' forests, we examined a simulation (the Local Wood Scenario) that increased the average annual harvest volume 285% above Recent Trends. This represents the equivalent of ~ 20% of current wood consumption levels in Massachusetts (Littlefield et al 2024). This scenario also uses the climate-oriented silvicultural prescriptions, which remove less wood per acre than conventional prescriptions. Therefore, increasing volume by 2.85 times required a 457% increase in area harvested. In the near term—i.e., by 2050—the Local Wood scenario reduced accumulated forest carbon stocks (all pools) by 16.65% in relation to Recent Trends. But, over time, the climate-oriented prescriptions succeeded in enhancing forest sequestration rate; and in 2100, the low disturbance simulation's forest carbon stocks were essentially the same (Figure 17*)*. Because increased harvesting in-state would presumably displace harvesting out of state (e.g., by 2050 the Local Wood scenario had produced ~63 $MMTCO_2e$ more wood products than Recent Trends), it is difficult to assess the full costs and benefits of the Local Wood scenarios, even for carbon impacts, since modeling the harvests outside of the state were outside the scope of this work. However, our analyses also show that improving wood utilization (e.g., more long-term use of wood products, improved production techniques, and increased salvage logging) have additional carbon benefits for all scenarios. Improved Wood Utilization can increase carbon stored by ~5 $MMTCO_2e$ by 2050 and ~13 $MMTCO_2e$ by 2100 in the low disturbance scenarios, primarily due to a shift of timber into additional long-term wood products. In the high disturbance scenarios these emissions could be reduced by 65 to 80 $MMTCO_2e$ by 2050 and 90 to 135 $MMTCO_2e$ by 2100, primarily due to a rapid increase in salvage logging that may mitigate some of the impacts of hurricanes.

While the Local Wood scenario modeled additional wood production from within the state with the intention of reducing demand for wood products from outside of the state, the Reserves Emphasis scenario focused on increasing the reserve area in the state while keeping production relatively similar to Recent Trends to limit potential leakage. However, due to the change in silvicultural prescriptions and increase in reserve area, we were unable to match wood production precisely and the Reserves Emphasis scenario produced slightly less wood products (5.42 MMTCO2e) than Recent Trends by 2050. If we assume no change in wood product demand, this gap in production would increase demands for wood production from outside of the state (leakage) and incur the emissions associated with sourcing these wood products and transporting them to the state. This leakage amount is greater than the difference in net sequestration between the Reserves Emphasis and Recent Trends scenarios (3.12 MMTCO2e), though the complex interplay between harvesting and sequestration makes it difficult to compare these values directly.

However, it is important to note that there are many non-carbon costs and benefits of harvesting related to changes in habitat, wood quality, nutrient cycling, and other forest conditions, alongside meeting some of the demand for wood products. Additionally, increasing harvest rates would present several social challenges that are largely outside the scope of this analysis. But one issue worth considering is whether enough Massachusetts landowners would be willing to harvest their forests—research suggests that most of the family forest owners who own the majority of forestland in the state do not cite timber harvesting as an important objective for their land (Caputo and Butler et al 2024).Therefore, alternate considerations that were not considered in these scenarios, such as reducing overall consumption, and in particular that of short-term products, may be an option for reducing overall land use emissions.

As for the ability for climate-oriented harvests to increase carbon stocks and sequestration rates, our simulations suggest that this is possible over longer periods of time (e.g., > 40 years). Forest productivity is, in part, a function of available light and growing space. Harvest prescriptions that increase these resources for retained trees by removing selected trees can enhance stand level productivity and, eventually, carbon stocks (Figure 36) (Carter et al 2017; D'Amato et al 2011). There is a complex interplay between carbon stocks, sequestration rates, and the ecological trajectories of forest stands, and, as exemplified in the low-disturbance scenarios, much of this interplay is still along a recovery trajectory following the previous centuries' intensive land use practices and disturbances. The simulated differences in forestry practices resulted in minor differences in overall forest carbon stocks and sequestration by 2100 in the low disturbance scenarios.

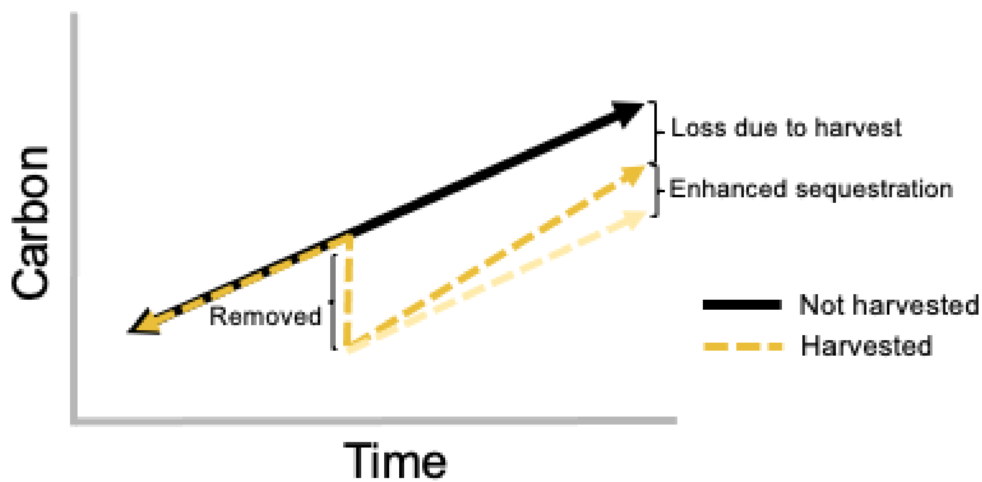

Figure 36*. In the short term, timber harvesting reduces stand-level live carbon stocks, increases in- and out-of-forest carbon emissions, and moves some harvested carbon into wood products. Harvesting can also increase subsequent rates of carbon sequestration as the remaining trees have more light and growing space. The time required for the increase in sequestration to make up for the lost stocks varies depending on harvest and site attributes.*

5.4 Forest Adaptive Capacity and Resiliency to Climate Change

The climate-oriented silvicultural prescriptions developed for this study were not necessarily focused on retaining more ecosystem carbon over the long-run. Silviculture that emphasizes increased accrual of forest ecosystem carbon in the aboveground live tree pool, over other values, may not be sustainable (e.g., Van Deusen and Roesch 2008, Van Deusen and Roesch 2009); and may compromise other forest ecosystem services like water quality, habitat, wood production, recreation, etc. (e.g., Woodall et al. 2011, de la Crétaz and Barten 2023, Nagel et al. 2017, Akresh et al. 2023). Instead, silvicultural prescriptions were developed—within the constraints of the modeling framework—that attempted to restore and sustain the integrity of forest ecosystems. By adjusting the silviculture to different regions of the Commonwealth and anticipating the conditions that would evolve in untreated areas, active management could complement management on the passive end of the management gradient by providing complexity at the appropriate scales (e.g., within types and patches of disturbance sized to that which is expected in an area, and across multiple overlapping patches over time given the annual probability of disturbance), in appropriate contexts and intervals. In this way, as wide an array of ecosystem services as possible could be sustained and stabilized, producing outcomes that reduced risk and increased future options (c.f. Franklin et al 2018, Palik and D'Amato 2017, Palik et al. 2020).

At a landscape scale, climate-oriented silviculture helps provide and maintain younger forest structural conditions that are currently at a deficit, while maintaining stable levels of older forest structural conditions at appropriate levels (e.g., Lorimer and White 2003, DeGraaf et al. 2006). Climate-oriented silviculture offers an important pathway to help accelerate the development of and sustain mature forest structural conditions by thinning to accelerate the growth and enhance the vigor of large trees, accelerating the development of multiple cohorts and complex canopy structures, and accelerating the recruitment of large pieces of down woody material (D'Amato and Catanzaro, 2022).

Climate-oriented silviculture, at a landscape scale, aids in the maintenance (Figure 34) and recruitment (Figure 35) of tree species that are projected to fare better under Massachusetts' future projected climate (https://www.fs.usda.gov/nrs/atlas/tree/). Silvicultural practices can be deliberately timed and patterned to facilitate the establishment and recruitment of specific species; natural disturbance regimes have been altered and, because of that and their unpredictable nature, do not occur in places or at times that can provide desired outcomes.

Results at a smaller scale, from case studies, show that silviculture can have an effect on outcomes. Outcomes of silvicultural treatments are different than a passive management approach—not always better or worse, but different—and, importantly, complementary and ideally part of an overall strategy designed to balance competing demands on a finite forest land base. Similarly, passively managed areas are not always an ideal condition because of the extreme alteration of the landscape and conditions such as herbivory and climate. The results show that deliberately undertaken management can have long-lasting and persistent effects under a wide range of circumstances, offering stability of community structure and ecosystem services in the face of disruption from pests, pathogens, severe weather, and climate change. Climate-oriented forestry also showed the ability to enhance attributes associated with the ability of forests to adapt to climate change, like species and structural richness and diversity (Appendix VIII, Case Studies 1-4). Just as climate-oriented silviculture can emphasize retention and recruitment of climate adapted species, it can help perpetuate communities with less favorable adaptiveness (e.g., Tables A14 and A15). Additionally, proactive silviculture may increase live carbon pool stability (e.g., Appendix VIII, Case Study 5) as compared to untreated areas. Areas with silvicultural treatments show reduced losses of live tree carbon to disturbances and more stable carbon accumulation trajectories, limiting subsequent emissions from tree mortality. While some of the carbon from harvesting is also emitted, a portion is also stored in wood products. This diversification of carbon storage approaches could help to mitigate risk to sequestered carbon from hurricanes and other disturbances.

5.5 Uncertainty, Limitations, and Opportunities for Future Research

The analyses presented here are among the most comprehensive and sophisticated applications of integrated ecosystem modeling for estimating future contributions of the land sector to state level climate mitigation goals (Lamb et al 2021). Nonetheless, like all modeling studies, these analyses have uncertainties, assumptions, limitations, and caveats that are important to understand. Many of the limitations have been discussed throughout this report. In addition, we list several below that we believe are particularly important for interpreting this report.

- *Multiple sources of uncertainty influence the estimates in this report.* In reviewing uncertainties within scenario analyses and models of socio-ecological systems in support of decision-making, Rounsevell et al (2021) identify three categories of uncertainty: Scenario Uncertainty, Model Uncertainty, and Decision Uncertainty. It is useful to consider this study using this lens. Scenario uncertainty refers to the inherent uncertainty within qualitative descriptions of alternative future human actions and decisions. Scenarios are not predictions but instead are used to bound a useful range of qualitative storylines. They can usefully be thought of as a rigorous way of asking "What if?" in terms of the way the future might unfold, based on specific assumptions about dominant social and ecological forces (Thompson et al 2020). Here we crafted scenarios based on observed recent trends, the interests of the Commonwealth, and of the stakeholders. Surely, things will turn out differently than the scenarios we portray here, and it is certainly possible that the scenarios will not capture the relevant dynamics that influence the landscape. Model Uncertainty refers to the representation of conditions and processes in models. This includes uncertainty in initial conditions, input variables, calculations, and includes amplification and propagation of errors across coupled models. To minimize model uncertainties, we used models and empirical data sources that have been rigorously calibrated, validated, and subject to peer review. Nonetheless, there are hundreds of interacting parameters and processes in our analytical framework and the potential uncertainties are manifest. We have done our best to minimize error and model uncertainty but know that this will forever be a work in progress. We make all our data and models open to the public and welcome anyone wishing to help improve our approach. Decision Uncertainty refers to how results of scenario and modeling studies are communicated and used in decision-making. This study may help to inform land use decision making, but it will not be used in isolation. None of the scenarios presented here are intended to serve as policy options. We worked very closely with EEA, DCR, and the stakeholders to ensure that the information is presented in a way that would be most useful. We met with EEA officials bi-monthly for more than two years and, while they did not influence the specific results, they dictated how the results were presented. And, again, we make all our outputs freely available to maximize their credibility and usefulness.
- *Soil carbon is perhaps the most significant omitted variable.* Soil carbon dynamics are difficult to measure, heterogenous across the landscape, and thus are challenging to characterize in a landscape model. Despite this, soil carbon is important; indeed, soil carbon represents approximately half of total ecosystem carbon in Massachusetts (Finzi et al 2020). Fortunately, from a modeling perspective, the gain and loss of soil carbon is much slower than for aboveground carbon pools. Soil carbon is not significantly affected (one way or the other) by timber harvesting in the northeastern U.S. (Nave et al 2024). In contrast, soil carbon is quite vulnerable to forest loss due to land-cover change, and slowly but consistently increases on reforested land in the region (Nave et al 2024). Developed environments typically have < 50% of the soil carbon found in adjacent forests – and dependent on the development intensity, can have much less than that (Racitti et al 2011; Contosta et al 2018). Little is known about the fate of soil carbon underneath ground-mount solar panels but, given the observed loss of soil carbon within soil warming

experiments at the Harvard Forest and elsewhere (e.g. Mellillo et al. 2017), it is reasonable to expect these stocks will decline over time. The upshot is that our estimated impacts of forest loss on carbon emissions should be assumed to be underestimates. Additionally, because we do not account for soil carbon accrual in reforested areas, these should also be interpreted as underestimates.

- *Modeling tree cohorts, as opposed to individual trees, limits our inference.* The LANDIS/PnET model simulates the growth, competition, and mortality of tree species within millions of pixels in this study, each containing multiple tree species. To make statewide simulations computationally tractable, the minimum modeling unit in LANDIS/PnET is a species-by-age cohort, not an individual tree (Scheller et al 2007). This is a necessary simplification; but the abstraction introduces some limitations to the interpretation of model outputs. Land managers do not operate on tree cohorts but instead make decisions based on characteristics of individual trees, including stem diameter, log quality, tree position within a stand (horizonal and vertical), and other details. The simulated silvicultural treatments therefore are coarse approximations of what would occur in the field.
- *Future climate impacts on ecosystems are uncertain.* We use an eco-physiological approach to modeling ecosystem response to a changing climate and disturbances, meaning we model plant mechanisms for cycling carbon, water, and nutrients as they use sunlight to convert atmospheric carbon dioxide to starches and sugars under variable climatic conditions. This process-based approach to modeling maximizes our ability to anticipate how plants will respond to climate change (Gustafson et al 2013). Nonetheless, we are simulating climatic conditions that have never been observed, and therefore there are uncertainties within the mechanisms themselves. One prominent example is the impact of increasing carbon dioxide concentrations in the atmosphere. To date, increasing carbon dioxide has served as a growth enhancement on eastern forests. Our simulations assume this will continue even as carbon dioxide rises to >475ppm late in the century. It is possible that the fertilization effect will saturate at some point (e.g. Wang et al 2020), but how and when this will occur is unknown.
- *Additional land sector ecosystem carbon dynamics.* This study addresses terrestrial carbon dynamics occurring on forest land and associated with changes in land-cover, including forest loss and land with new forest and tree cover. It uses static carbon density coefficients on all non-forest land cover and does not simulate carbon sequestration or emissions within these cover types, including on wetlands, croplands, grasslands, and at least some portion of settlements (i.e. trees and forests in and around developed areas). Settlement biomass growth in particular represents the most significant category of carbon removal after forest land in Massachusetts' natural and working lands greenhouse gas inventory (EEA 2022b). While some of this growth was modeled here (e.g. new urban tree planting), complete coverage of biological carbon dynamics in developed areas was outside this study's scope, so settlements represent an additional area of carbon fluxes to be considered.
- *Simulated changes in commercial timber harvest*. The analysis is limited to Massachusetts' land sector and does not quantify the potential for out of state leakage (e.g., an increase in out-of-state harvesting to make up for a decrease of in state harvest, or vice-versa) nor does it address any potential substitution effects (e.g., a change in emissions associated with substituting concrete or steel in response to available wood building materials c.f. Pett-Ridge et al 2023)

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Appendices

Appendix I: Initial tree species abundance within landscape simulations

Table A1. *Initial tree species abundance in landscape simulations in terms of total statewide aboveground live carbon.*

Species Code	Genus	Species	Statewide Aboveground Live Carbon (MMTCO2e)	Percent of Total Aboveground Live Carbon
ACRU	Acer	rubrum	55.63	17.63
QURU	Quercus	rubra	53.76	17.04
PIST	Pinus	strobus	47.03	14.9
ACSA	Acer	saccharum	20.96	6.64
TSCA	Tsuga	canadensis	19.91	6.31
QUVE	Quercus	velutina	18.42	5.84
QUCO	Quercus	coccinea	15.29	4.85
QUAL	Quercus	alba	14.92	4.73
FRAM	Fraxinus	americana	12.64	4.00
BELE	Betula	lenta	11.21	3.55
FAGR	Fagus	grandifolia	10.75	3.41
PRSE	Prunus	serotina	9.72	3.08
BEAL	Betula	alleghaniensis	5.94	1.88
PIRI	Pinus	rigida	4.11	1.30
QUPR	Quercus	prinus	3.78	1.20
CAGL	Carya	glabra	2.77	0.88
PIRU	Picea	rubens	1.32	0.42
POTR	Populus	tremuloides	1.25	0.40
BEPA	Betula	papyrifera	1.24	0.39
OSVI	Ostrya	virginiana	0.97	0.31
TIAM	Tilia	americana	0.79	0.25
ABBA	Abies	balsamea	0.68	0.22
POGR	Populus	grandidentata	0.67	0.21
BEPO	Betula	populifolia	0.46	0.15
ULAM	Ulmus	americana	0.45	0.14
PIRE	Pinus	resinosa	0.43	0.13
THOC	Thuja	occidentalis	0.19	0.06
FRNI	Fraxinus	nigra	0.14	0.04
PIGL	Picea	glauca	0.05	0.02
LALA	Larix	laricina	0.05	0.01
PIMA	Picea	mariana	0.03	0.01
POBA	Populus	balsamifera	0.01	0.00

Appendix II: Harvest Prescriptions

Climate-oriented forestry harvest prescriptions

State staff performed a literature review with the aim of identifying recommendations on the proportion of forest land in different structural stages. The findings could generally be grouped into those identifying a historic range of variability (i.e., retrospective, see e.g. Lorimer and White 2003), and those that identified a range based on current and future conditions (i.e., prospective, see e.g. DeGraaf et al. 1992, Litvaitis 2003, DeGraaf et al. 2006, Litvaitis et al. 2021). Staff recommended rates of application of different silvicultural systems (even-aged and uneven-aged management) that would result, over the long run, in landscape-scale conditions in different regions of Massachusetts roughly in the middle of the two ranges. These were then further adjusted in different scenarios to meet different constraints. For example, as originally developed, the CSF prescriptions did not remove enough wood to meet the increased demand in the local wood oriented scenarios, so adjustments were made. It was also noted that the initial communities landscape differed from other estimates of Massachusetts' forested landscape in several critical ways that affected prescription calibration. First, the species composition was different because the list of modeled species was a subset of actual species, and biomass from unmodeled species was not assigned to a modeled surrogate. For example, pignut hickory was the only hickory species modeled, which affected the composition of certain important natural communities such as oak-hickory and sugar maple-oak-hickory. This would also affect the proportion of species' biomass removed when designing prescriptions that would sustain those communities. Next, the mean forest density was different. The USFS FIA and TREEMAP datasets point to Massachusetts forests' being more densely stocked than the initial community data indicated, with live tree basal area (one of the key metrics used in developing and implementing silvicultural prescriptions) 28% greater, as well as live tree carbon density. This resulted in less biomass being initially removed in modeled prescriptions to meet silvicultural, resiliency, and adaptation objectives relating to tree growing space and regeneration, than would be required in reality.

Species retention priorities by broad ecoregion

The next step in prescription development was to assign a proportion of biomass removed within each species and age class. The most readily available information to calibrate these proportions was from the initial communities data. Unfortunately, a good deal of silvicultural prescription writing is not predicated on proportional removal from pre-harvest conditions, but rather creation of specific conditions (e.g., retaining 70 ft^2/ac of basal area per acre, instead of removing 40% of basal area) – so the prescriptions could not be updated as conditions evolved within the model.

***Table A2**. Species retention priorities by broad ecoregion*

Common name	Genus	Species	Retention priority		
			West	Central	East
balsam fir	*Abies*	*balsamea*	high	high	high
tamarack	*Larix*	*laricina*	high	high	high
black spruce	*Picea*	*mariana*	high	high	high
red spruce	*Picea*	*rubens*	high	high	high
red pine	*Pinus*	*resinosa*	neutral	moderately low	low
pitch pine	*Pinus*	*rigida*	high	high	high
eastern white pine	*Pinus*	*strobus*	moderately high	moderately high	low
eastern hemlock	*Tsuga*	*canadensis*	moderately high	moderately high	high
red maple	*Acer*	*rubrum*	low	low	low
sugar maple	*Acer*	*saccharum*	high	high	high
yellow birch	*Betula*	*alleghaniensis*	moderately high	moderately high	high
sweet birch	*Betula*	*lenta*	moderately high	low	moderately high
paper birch	*Betula*	*papyrifera*	neutral	neutral	high
gray birch	*Betula*	*populifolia*	neutral	neutral	moderately low
pignut hickory	*Carya*	*glabra*	high	high	high
American beech	*Fagus*	*grandifolia*	moderately low	moderately low	moderately high
white ash	*Fraxinus*	*americana*	neutral	neutral	high
black ash	*Fraxinus*	*nigra*	high	high	high
hophornbeam	*Ostrya*	*virginiana*	high	high	high
bigtooth aspen	*Populus*	*grandidentata*	low	low	moderately high
quaking aspen	*Populus*	*tremuloides*	low	low	high
black cherry	*Prunus*	*serotina*	moderately high	moderately low	high
white oak	*Quercus*	*alba*	high	high	high
scarlet oak	*Quercus*	*coccinea*	moderately high	moderately high	neutral
chestnut oak	*Quercus*	*prinus*	high	high	moderately high
northern red oak	*Quercus*	*rubra*	high	high	high
black oak	*Quercus*	*velutina*	moderately high	moderately high	neutral
American basswood	*Tilia*	*americana*	moderately low	moderately low	high
American elm	*Ulmus*	*americana*	high	high	high

Species retention preferences (Table A2) were set using the above framework of trying to balance what would be projected to be happening in areas allocated to reserves in the model, with what silviculture could accomplish outside those areas. For example, eastern white pine tended to be more strongly favored for retention in the western part of the state than in the east, where it was viewed as a successional competitor with pitch pine. Another example is favoring aspen for removal, precisely to create the disturbance it needs to be regenerated, and provide the concomitant habitat benefits. A final example is favoring the removal of red maple, since, despite its predicted high suitability to the expected future climate in Massachusetts, it is a generalist and lacks strong long-term carbon flux and storage advantages given its current and expected usage patterns in wood products.

It was assumed that all area harvested was not subject to legal, physical, or social constraints on harvest intensity. For example, the Forest Cutting Practices Act (FCPA) specifies that within filter and buffer strips no more than 50% of the basal area shall be cut at any one time. Water features to which filter strips would have been applied in real life were not spatially modeled. However, the intensity of removals was not prorated by the area (one comprehensive estimate from 2012 was that 27% of unreserved forest land had such constraints), under which such intensities would have been in violation of the FCPA. Thus, harvest intensity in the more harvest intensive scenarios may be overestimated compared to a realized application of harvests where these constraints apply.

These prescriptions were applied to the tallied trees on each FIA plot used in the initial communities dataset, selecting tallied trees and removing or retaining proportions of the trees per acre they represented based on the sample design. The removed and retained within each combination of modeled species and age class was calculated, using as similar algorithms as possible (that is, using the FIA plot site tree data, the Forest Vegetation Simulator's site index conversion algorithm, and appropriate site index curves and tree height to estimate tally tree age) as were used to develop the initial communities dataset. The FIA's Component Ratio Method (CRM) was used to estimate above ground live tree biomass (as the study commenced before the NVSB estimators were finalized). Mean removal intensities for each combination of modeled species and age class, for use in the prescriptions, were obtained by weighting the results from each plot by the number of times it was used within each region. It was noted that the initial communities dataset did not include any biomass in the youngest age cohort, whereas the prescription calibration dataset did through the inclusion of tallied seedling data on FIA plots.

The prescriptions were calibrated to the initial community dataset. The process of assigning biomass to cohorts using the above process resulted in different stand conditions than would exist within a model run after a disturbance. There was no ability to refine or balance prescriptions to this discrepancy. Thus, it is implied that the inertia of the initial landscape and relatively low disturbance rates would be enough to keep those prescriptions accurate over the entire modeling temporal horizon. There was also not enough time provided to evaluate whether these prescriptions had the intended effect within the model and make any adjustments. Finally, in analyzing the modeled results of the prescriptions, it was noted that modeled post-harvest biomass recovery rates tended to be lower than empirical data from FIA and CFI plots when comparing similar harvest intensities.

Harvest prescription entry requirements

Each of the defined prescriptions then needed to be translated into LANDIS-II/Biomass Harvest prescriptions and applied across the landscape. Biomass Harvest (extension) uses stand entry requirements to select forest pixels for the application of each harvest prescription. Table A3 summarizes the main components of the stand entry or selection criteria for each of the harvest prescriptions. There are two types of harvest prescriptions, Baseline and Climate-oriented, where Baseline prescriptions were used in the Recent Trends scenarios, and the Climate-oriented prescriptions were used in all other scenarios.

The minimum age of oldest cohort restricts a prescription to a pixel with a cohort of at least that age, so a pixel with only younger cohorts would not be eligible for that prescription (e.g., a pixel with all cohorts younger than 100 years would not be eligible for an "Uneven" or uneven-aged prescription). The minimum time since last harvest restricts harvests on pixels that were recently harvested by a set number of years (e.g., a pixel harvested 20 years prior is not eligible for a high-grade). The min and max patch sizes represent the smallest and largest sizes allowed for each harvest type. The % species to remove columns show the average amount of species removed for each age range of cohorts by prescription. In the baseline scenarios, harvests were simplified to represent a range of average harvests seen on the landscape, so percentages of species removed were split by high and low value species (as described in the LSR). The newly defined Climate-oriented prescriptions have more refined species and age class specific removals, so the average % removed by age range is reported rather than by high or low-value groups.

Table A3. *Stand entry requirements by prescription. OSR = overstory removal, GRPSEL = group selection, FSI = forest stand improvement.*

		Entry Requirements							
Harvest Type Simulation	**Rx Name**	Min. Age of Oldest Cohort	Min. Time Since Last Harvest	Min. Patch Size (ha)	Max. Patch Size (ha)**	% Low Value Species to Remove	% High Value Species to Remove	Mean (std. dev.) % Species to Remove	Age Range
Baseline	Thin	50	15	2	28	50	30		>50
Baseline	OSR* High Intensity	100	15	2	57	100	100		20-100
						97	95		>100
Baseline	OSR* Low Intensity	100	15	2	57	90	90		20-100
						90	65		>100
Baseline	Uneven	100	50	2	30	50	50		20-50
						75	50		50-100
						75	75		>100
Baseline	High-grade	60	40	2	42	40	80		>60
Climate-oriented	GRPSEL 25 yr. rotation	50	25	1.01	23.61			35 (16)	<10
								35 (12)	10-25
								28 (11)	26-50
								24 (11)	50-75
								24 (13)	75-100
								22 (13)	100-125
								24 (17)	125-175
								23 (18)	>175
Climate-oriented	GRPSEL40 yr. rotation	100	40	1.01	24.96			42 (10)	<10
								41 (6)	10-25
								34 (5)	26-50
								33 (6)	50-75
								34 (5)	75-100
								32 (7)	100-125
								33 (9)	125-175
								31 (11)	>175

Climate-oriented	Targeted OSR intense	40	25	1.01	4.39		88 (23)	<10
							100 (0)	10-25
							99 (1)	26-50
							98 (11)	50-75
							99 (2)	75-100
							96 (15)	100-125
							95 (18)	125-175
							91 (26)	>175
Climate-oriented	OSR	40	25	1.01	4.39		84 (23)	<10
							91 (14)	10-25
							86 (13)	26-50
							82 (18)	50-75
							79 (23)	75-100
							77 (23)	100-125
							78 (25)	125-175
							73 (31)	>175
Climate-oriented	THIN	40	20	1.01	28.33		55 (31)	<10
							47 (25)	10-25
							29 (23)	26-50
							21 (22)	50-75
							20 (25)	75-100
							16 (22)	100-125
							16 (22)	125-175
							17 (27)	>175
Climate-oriented	Targeted FSI	1	25	1.01	28.33		64 (26)	<10
							64 (26)	10-25
						hemlock/ash only	95 (0)	26-50
						hemlock/ash only	95 (0)	50-75
						hemlock/ash only	95 (0)	75-100
						hemlock/ash only	95 (0)	100-125
						hemlock/ash only	95 (0)	125-175
						hemlock/ash only	95 (0)	>175
Climate-oriented	Targeted OSR	1	25	1.01	28.33		86 (23)	<10
							91 (12)	10-25
							89 (10)	26-50
							86 (14)	50-75
							83 (22)	75-100
							81 (17)	100-125
							77 (24)	125-175
							76 (30)	>175

Appendix III: Harvested Wood Products

Table A4. *Harvested Wood Product Categories*

Timber Product	Primary Product	End Use Product	Discard Product
hardwood, sawtimber	fuelwood and other	fuelwood and other	fuelwood
hardwood, sawtimber	lumber	manufacturing, other manufacturing	lumber
hardwood, sawtimber	lumber	rail and railcar, n/a	lumber
hardwood, sawtimber	lumber	packaging and shipping, n/a	lumber
hardwood, sawtimber	lumber	manufacturing, furniture	lumber
hardwood, sawtimber	lumber	other, n/a	lumber
hardwood, sawtimber	lumber	new nonresidential, other	lumber
hardwood, sawtimber	lumber	new nonresidential, new nonresidential buildings	lumber
hardwood, sawtimber	lumber	residential r and r, n/a	lumber
hardwood, sawtimber	lumber	new housing, manufactured housing	lumber
hardwood, sawtimber	lumber	new housing, single family	lumber
hardwood, sawtimber	lumber	new housing, multifamily	lumber
hardwood, sawtimber	non-structural panels	manufacturing, other manufacturing	plywood
hardwood, sawtimber	non-structural panels	new housing, multifamily	plywood
hardwood, sawtimber	non-structural panels	new housing, single family	plywood
hardwood, sawtimber	non-structural panels	residential r and r, n/a	plywood
hardwood, sawtimber	non-structural panels	new nonresidential, new nonresidential buildings	plywood
hardwood, sawtimber	non-structural panels	new nonresidential, other	plywood
hardwood, sawtimber	non-structural panels	rail and railcar, n/a	plywood
hardwood, sawtimber	non-structural panels	manufacturing, furniture	plywood
hardwood, sawtimber	non-structural panels	new housing, manufactured housing	plywood
hardwood, sawtimber	non-structural panels	packaging and shipping, n/a	plywood
hardwood, sawtimber	non-structural panels	other, n/a	plywood
hardwood, sawtimber	oriented strand board (OSB)	new housing, multifamily	plywood
hardwood, sawtimber	oriented strandboard (OSB)	rail and railcar, n/a	plywood
hardwood, sawtimber	oriented strandboard (OSB)	new housing, single family	plywood
hardwood, sawtimber	oriented strandboard (OSB)	new housing, manufactured housing	plywood
hardwood, sawtimber	oriented strandboard (OSB)	manufacturing, furniture	plywood
hardwood, sawtimber	oriented strandboard (OSB)	new nonresidential, new nonresidential buildings	plywood

hardwood, sawtimber	oriented strandboard (OSB)	manufacturing, other manufacturing	plywood
hardwood, sawtimber	oriented strandboard (OSB)	packaging and shipping, n/a	plywood
hardwood, sawtimber	oriented strandboard (OSB)	other, n/a	plywood
hardwood, sawtimber	oriented strandboard (OSB)	residential r and r, n/a	plywood
hardwood, sawtimber	oriented strandboard (OSB)	new nonresidential, other	plywood
hardwood, sawtimber	other industrial products	other industrial products	wood
hardwood, sawtimber	plywood	new housing, manufactured housing	plywood
hardwood, sawtimber	plywood	new housing, multifamily	plywood
hardwood, sawtimber	plywood	residential r and r, n/a	plywood
hardwood, sawtimber	plywood	new nonresidential, new nonresidential buildings	plywood
hardwood, sawtimber	plywood	new nonresidential, other	plywood
hardwood, sawtimber	plywood	rail and railcar, n/a	plywood
hardwood, sawtimber	plywood	manufacturing, furniture	plywood
hardwood, sawtimber	plywood	manufacturing, other manufacturing	plywood
hardwood, sawtimber	plywood	packaging and shipping, n/a	plywood
hardwood, sawtimber	plywood	other, n/a	plywood
hardwood, sawtimber	plywood	new housing, single family	plywood
hardwood, sawtimber	wood pulp	wood pulp	paper
softwood, sawtimber	fuelwood and other	fuelwood and other	fuelwood
softwood, sawtimber	lumber	residential r and r, n/a	lumber
softwood, sawtimber	lumber	packaging and shipping, n/a	lumber
softwood, sawtimber	lumber	manufacturing, other manufacturing	lumber
softwood, sawtimber	lumber	manufacturing, furniture	lumber
softwood, sawtimber	lumber	rail and railcar, n/a	lumber
softwood, sawtimber	lumber	new nonresidential, new nonresidential buildings	lumber
softwood, sawtimber	lumber	other, n/a	lumber
softwood, sawtimber	lumber	new housing, multifamily	lumber
softwood, sawtimber	lumber	new housing, manufactured housing	lumber
softwood, sawtimber	lumber	new housing, single family	lumber
softwood, sawtimber	lumber	new nonresidential, other	lumber
softwood, sawtimber	non-structural panels	manufacturing, other manufacturing	plywood
softwood, sawtimber	non-structural panels	other, n/a	plywood
softwood, sawtimber	non-structural panels	new housing, single family	plywood
softwood, sawtimber	non-structural panels	rail and railcar, n/a	plywood
softwood, sawtimber	non-structural panels	packaging and shipping, n/a	plywood

softwood, sawtimber	non-structural panels	new housing, manufactured housing	plywood
softwood, sawtimber	non-structural panels	residential r and r, n/a	plywood
softwood, sawtimber	non-structural panels	new nonresidential, other	plywood
softwood, sawtimber	non-structural panels	manufacturing, furniture	plywood
softwood, sawtimber	non-structural panels	new housing, multifamily	plywood
softwood, sawtimber	non-structural panels	new nonresidential, new nonresidential buildings	plywood
softwood, sawtimber	oriented strand board (OSB)	rail and railcar, n/a	plywood
softwood, sawtimber	oriented strandboard (OSB)	new nonresidential, other	plywood
softwood, sawtimber	oriented strandboard (OSB)	new housing, manufactured housing	plywood
softwood, sawtimber	oriented strandboard (OSB)	residential r and r, n/a	plywood
softwood, sawtimber	oriented strandboard (OSB)	new nonresidential, new nonresidential buildings	plywood
softwood, sawtimber	oriented strandboard (OSB)	other, n/a	plywood
softwood, sawtimber	oriented strandboard (OSB)	packaging and shipping, n/a	plywood
softwood, sawtimber	oriented strandboard (OSB)	new housing, multifamily	plywood
softwood, sawtimber	oriented strandboard (OSB)	new housing, single family	plywood
softwood, sawtimber	oriented strandboard (OSB)	manufacturing, other manufacturing	plywood
softwood, sawtimber	oriented strandboard (OSB)	manufacturing, furniture	plywood
softwood, sawtimber	other industrial products	other industrial products	wood
softwood, sawtimber	plywood	residential r and r, n/a	plywood
softwood, sawtimber	plywood	manufacturing, furniture	plywood
softwood, sawtimber	plywood	new housing, single family	plywood
softwood, sawtimber	plywood	new housing, multifamily	plywood
softwood, sawtimber	plywood	manufacturing, other manufacturing	plywood
softwood, sawtimber	plywood	other, n/a	plywood
softwood, sawtimber	plywood	rail and railcar, n/a	plywood
softwood, sawtimber	plywood	new nonresidential, new nonresidential buildings	plywood
softwood, sawtimber	plywood	new housing, manufactured housing	plywood
softwood, sawtimber	plywood	packaging and shipping, n/a	plywood
softwood, sawtimber	plywood	new nonresidential, other	plywood
softwood, sawtimber	wood pulp	wood pulp	paper
hardwood, poletimber	fuelwood and other	fuelwood and other	fuelwood
hardwood, poletimber	lumber	rail and railcar, n/a	lumber
hardwood, poletimber	lumber	packaging and shipping, n/a	lumber
hardwood, poletimber	lumber	other, n/a	lumber

hardwood, poletimber	lumber	manufacturing, furniture	lumber
hardwood, poletimber	lumber	new housing, multifamily	lumber
hardwood, poletimber	lumber	new nonresidential, other	lumber
hardwood, poletimber	lumber	new housing, single family	lumber
hardwood, poletimber	lumber	new nonresidential, new nonresidential buildings	lumber
hardwood, poletimber	lumber	new housing, manufactured housing	lumber
hardwood, poletimber	lumber	residential r and r, n/a	lumber
hardwood, poletimber	lumber	manufacturing, other manufacturing	lumber
hardwood, poletimber	non-structural panels	manufacturing, other manufacturing	plywood
hardwood, poletimber	non-structural panels	new housing, multifamily	plywood
hardwood, poletimber	non-structural panels	other, n/a	plywood
hardwood, poletimber	non-structural panels	residential r and r, n/a	plywood
hardwood, poletimber	non-structural panels	new nonresidential, new nonresidential buildings	plywood
hardwood, poletimber	non-structural panels	packaging and shipping, n/a	plywood
hardwood, poletimber	non-structural panels	new nonresidential, other	plywood
hardwood, poletimber	non-structural panels	new housing, single family	plywood
hardwood, poletimber	non-structural panels	new housing, manufactured housing	plywood
hardwood, poletimber	non-structural panels	manufacturing, furniture	plywood
hardwood, poletimber	non-structural panels	rail and railcar, n/a	plywood
hardwood, poletimber	oriented strandboard (OSB)	manufacturing, other manufacturing	plywood
hardwood, poletimber	oriented strandboard (OSB)	packaging and shipping, n/a	plywood
hardwood, poletimber	oriented strandboard (OSB)	other, n/a	plywood
hardwood, poletimber	oriented strandboard (OSB)	manufacturing, furniture	plywood
hardwood, poletimber	oriented strandboard (OSB)	rail and railcar, n/a	plywood
hardwood, poletimber	oriented strandboard (OSB)	new nonresidential, new nonresidential buildings	plywood
hardwood, poletimber	oriented strandboard (OSB)	new housing, single family	plywood
hardwood, poletimber	oriented strandboard (OSB)	new housing, manufactured housing	plywood
hardwood, poletimber	oriented strandboard (OSB)	residential r and r, n/a	plywood
hardwood, poletimber	oriented strandboard (OSB)	new nonresidential, other	plywood
hardwood, poletimber	oriented strandboard (OSB)	new housing, multifamily	plywood
hardwood, poletimber	other industrial products	other industrial products	wood
hardwood, poletimber	plywood	residential r and r, n/a	plywood
hardwood, poletimber	plywood	packaging and shipping, n/a	plywood
hardwood, poletimber	plywood	new housing, manufactured housing	plywood

hardwood, poletimber	plywood	new housing, single family	plywood
hardwood, poletimber	plywood	new housing, multifamily	plywood
hardwood, poletimber	plywood	other, n/a	plywood
hardwood, poletimber	plywood	manufacturing, other manufacturing	plywood
hardwood, poletimber	plywood	rail and railcar, n/a	plywood
hardwood, poletimber	plywood	new nonresidential, new nonresidential buildings	plywood
hardwood, poletimber	plywood	manufacturing, furniture	plywood
hardwood, poletimber	plywood	new nonresidential, other	plywood
hardwood, poletimber	wood pulp	wood pulp	paper
softwood, poletimber	fuelwood and other	fuelwood and other	fuelwood
softwood, poletimber	lumber	residential r and r, n/a	lumber
softwood, poletimber	lumber	manufacturing, furniture	lumber
softwood, poletimber	lumber	new housing, manufactured housing	lumber
softwood, poletimber	lumber	new housing, multifamily	lumber
softwood, poletimber	lumber	new nonresidential, new nonresidential buildings	lumber
softwood, poletimber	lumber	new nonresidential, other	lumber
softwood, poletimber	lumber	manufacturing, other manufacturing	lumber
softwood, poletimber	lumber	packaging and shipping, n/a	lumber
softwood, poletimber	lumber	other, n/a	lumber
softwood, poletimber	lumber	new housing, single family	lumber
softwood, poletimber	lumber	rail and railcar, n/a	lumber
softwood, poletimber	non-structural panels	new housing, single family	plywood
softwood, poletimber	non-structural panels	manufacturing, furniture	plywood
softwood, poletimber	non-structural panels	other, n/a	plywood
softwood, poletimber	non-structural panels	packaging and shipping, n/a	plywood
softwood, poletimber	non-structural panels	new nonresidential, new nonresidential buildings	plywood
softwood, poletimber	non-structural panels	manufacturing, other manufacturing	plywood
softwood, poletimber	non-structural panels	new nonresidential, other	plywood
softwood, poletimber	non-structural panels	residential r and r, n/a	plywood
softwood, poletimber	non-structural panels	new housing, multifamily	plywood
softwood, poletimber	non-structural panels	rail and railcar, n/a	plywood
softwood, poletimber	non-structural panels	new housing, manufactured housing	plywood
softwood, poletimber	oriented strandboard (OSB)	manufacturing, furniture	plywood
softwood, poletimber	oriented strandboard (OSB)	manufacturing, other manufacturing	plywood

softwood, poletimber	oriented strandboard (OSB)	new nonresidential, other	plywood
softwood, poletimber	oriented strandboard (OSB)	new housing, single family	plywood
softwood, poletimber	oriented strandboard (OSB)	new housing, multifamily	plywood
softwood, poletimber	oriented strandboard (OSB)	new housing, manufactured housing	plywood
softwood, poletimber	oriented strandboard (OSB)	residential r and r, n/a	plywood
softwood, poletimber	oriented strandboard (OSB)	rail and railcar, n/a	plywood
softwood, poletimber	oriented strandboard (OSB)	packaging and shipping, n/a	plywood
softwood, poletimber	oriented strandboard (OSB)	other, n/a	plywood
softwood, poletimber	oriented strandboard (OSB)	new nonresidential, new nonresidential buildings	plywood
softwood, poletimber	other industrial products	other industrial products	wood
softwood, poletimber	plywood	rail and railcar, n/a	plywood
softwood, poletimber	plywood	new nonresidential, other	plywood
softwood, poletimber	plywood	other, n/a	plywood
softwood, poletimber	plywood	manufacturing, other manufacturing	plywood
softwood, poletimber	plywood	new nonresidential, new nonresidential buildings	plywood
softwood, poletimber	plywood	packaging and shipping, n/a	plywood
softwood, poletimber	plywood	new housing, manufactured housing	plywood
softwood, poletimber	plywood	new housing, multifamily	plywood
softwood, poletimber	plywood	new housing, single family	plywood
softwood, poletimber	plywood	manufacturing, furniture	plywood
softwood, poletimber	plywood	residential r and r, n/a	plywood
softwood, poletimber	wood pulp	wood pulp	paper
hardwood, poles	hardwood, poles	hardwood, poles	wood
softwood, poles	softwood, poles	softwood, poles	wood
hardwood, pilings	hardwood, pilings	hardwood, pilings	wood
softwood, pilings	softwood, pilings	softwood, pilings	wood
hardwood, pulp	hardwood, pulp	hardwood, pulp	paper
softwood, pulp	softwood, pulp	softwood, pulp	paper
hardwood, posts	hardwood, posts	hardwood, posts	wood
softwood, posts	softwood, posts	softwood, posts	wood
hardwood, fuelwood	hardwood, fuelwood	hardwood, fuelwood	fuelwood
softwood, fuelwood	softwood, fuelwood	softwood, fuelwood	fuelwood
hardwood, non-sawtimber	hardwood, non-sawtimber	hardwood, non-sawtimber	wood
softwood, non-sawtimber	softwood, non-sawtimber	softwood, non-sawtimber	wood

hardwood, ties	hardwood, ties	hardwood, ties	wood
softwood, ties	softwood, ties	softwood, ties	wood
hardwood, coop bolts	hardwood, coop bolts	hardwood, coop bolts	wood
softwood, coop bolts	softwood, coop bolts	softwood, coop bolts	wood
hardwood, acid/dist.	hardwood, acid/dist.	hardwood, acid/dist.	wood
softwood, acid/dist.	softwood, acid/dist.	softwood, acid/dist.	wood
hardwood, float logs	hardwood, float logs	hardwood, float logs	wood
softwood, float logs	softwood, float logs	softwood, float logs	wood
hardwood, trap float	hardwood, trap float	hardwood, trap float	wood
softwood, trap float	softwood, trap float	softwood, trap float	wood
hardwood, misc-conv.	hardwood, misc-conv.	hardwood, misc-conv.	wood
softwood, misc-conv.	softwood, misc-conv.	softwood, misc-conv.	wood
hardwood, nav stores	hardwood, nav stores	hardwood, nav stores	wood
softwood, nav stores	softwood, nav stores	softwood, nav stores	wood
hardwood, cull logs	hardwood, cull logs	hardwood, cull logs	wood
softwood, cull logs	softwood, cull logs	softwood, cull logs	wood
hardwood, sm rnd wd	hardwood, sm rnd wd	hardwood, sm rnd wd	wood
softwood, sm rnd wd	softwood, sm rnd wd	softwood, sm rnd wd	wood
hardwood, grn bio cv	hardwood, grn bio cv	hardwood, grn bio cv	wood
softwood, grn bio cv	softwood, grn bio cv	softwood, grn bio cv	wood
hardwood, dry bio cv	hardwood, dry bio cv	hardwood, dry bio cv	wood
softwood, dry bio cv	softwood, dry bio cv	softwood, dry bio cv	wood
hardwood, sp wood pr	hardwood, sp wood pr	hardwood, sp wood pr	wood
softwood, sp wood pr	softwood, sp wood pr	softwood, sp wood pr	wood

Appendix IV: Terrestrial Carbon in Developed Land

Following the LSR and (Raciti et al. 2012), pixels classed as "developed" in the 2020 LCMAP were assigned to one of four levels of development intensity based on the level of imperviousness surrounding that pixel. For each LCMAP development pixel, we calculated the mean percent impervious surface within a 990m moving window using the NLCD percent impervious layer for 2019. We then classified the LCMAP developed pixels into intensity levels using the imperiousness thresholds detailed in Table A4. Based on an extensive literature review, we assigned carbon density estimates for each of the four development classes (Figure A1 & A2). We then used the mean value for each class, with the highest density class (e.g. bare parking lots or rooftops) assumed to be zero. Unlike forest carbon, carbon densities within the developed environment are held constant throughout the simulations, with the exception of carbon accrual resulting from urban tree planting described in section 3.7.

All new development was assumed to clear all vegetation from the site resulting in zero above ground live carbon left on the cell. The carbon from the cleared vegetation was simulated in two ways: 1) as if the carbon from the cleared vegetation is immediately emitted, and 2) as if the timber from the clearing entered the Improved Wood Utilization variant of the HWP model. The immediate emissions were used to quantify the largest emissions possible for the land conversion, and the Improved Wood Utilization scenario was used to quantify the emissions reductions that could be achieved if all land clearing for development included a timber harvest.

Table A5. *Classification of LCMAP developed class based on NLCD thresholds.*

NLCD thresholds	LCMAP reclassification	Literature Review Sources	$MTCO_2e$/ha	$MTCO_2e$/acre
Developed, Open Space, < 20% impervious	Developed, Low Density	Hardiman et al. 2017 Raciti et al. 2012 Rao et al. 2013 Thompson et al. 2020.	178.4	72.2
Developed, Low Intensity, 20 - 49% impervious	Developed, Medium Density	Briber et al. 2015 Hardiman et al. 2017 Raciti et al. 2012 Rao et al. 2013 Thompson et al. 2020.	136.5	55.2
Developed, Medium Intensity, 50 - 79% impervious	Developed, High Density	Hardiman et al. 2017 Raciti et al. 2012 Rao et al. 2013 Thompson et al. 2020.	72.3	29.3
Developed, High Intensity, >80%	Developed, Highest Density		0.0	0.0

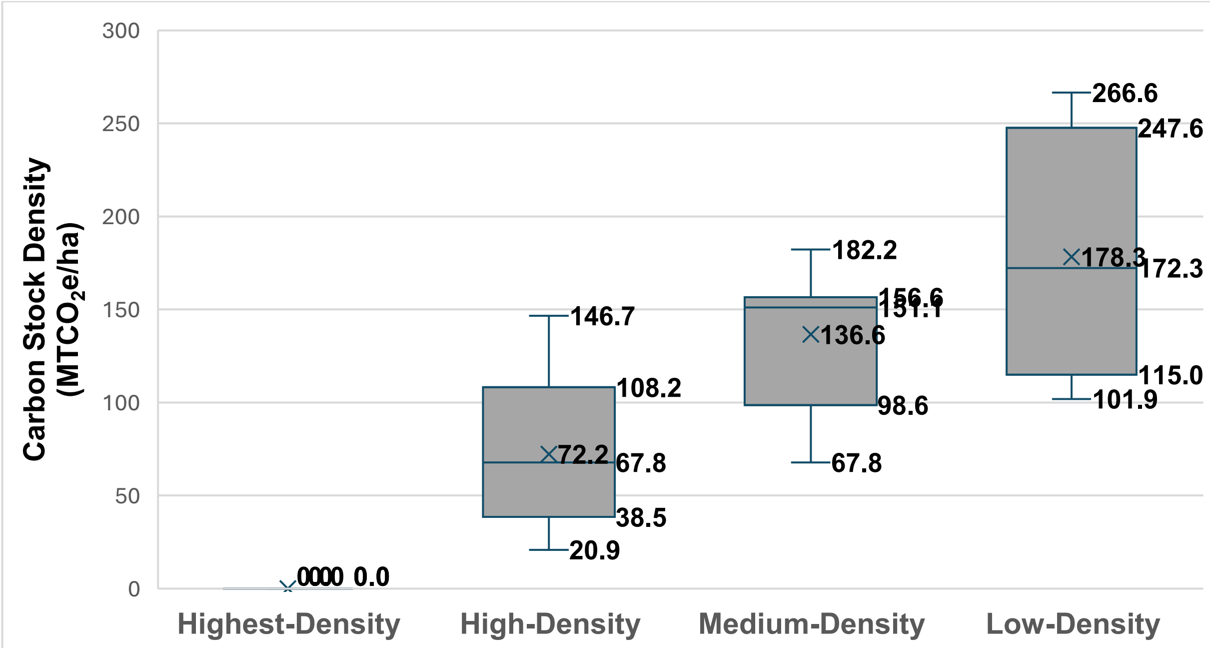

Figure A1. *Literature review of live above ground carbon density in the developed environment. Mean carbon density was used for each level of development intensity.*

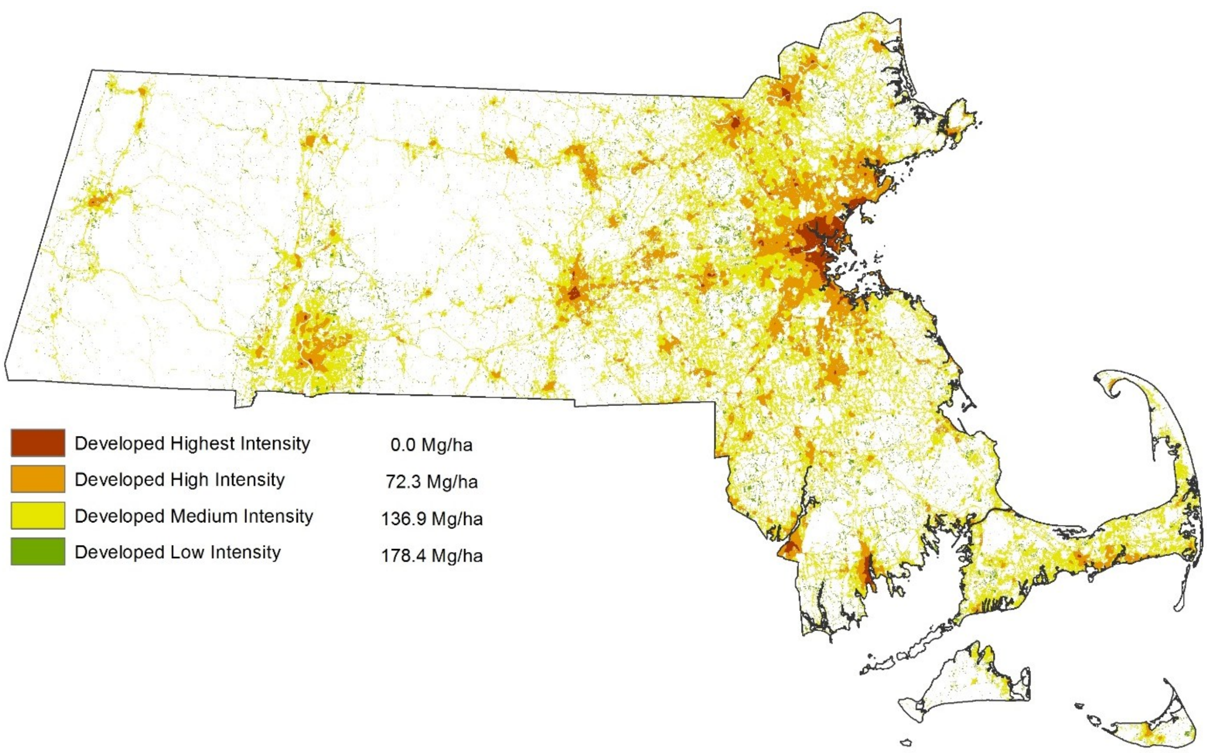

Figure A2. *Spatial distribution of live above ground carbon in the four developed land cover classes.*

Appendix V: Solar Siting

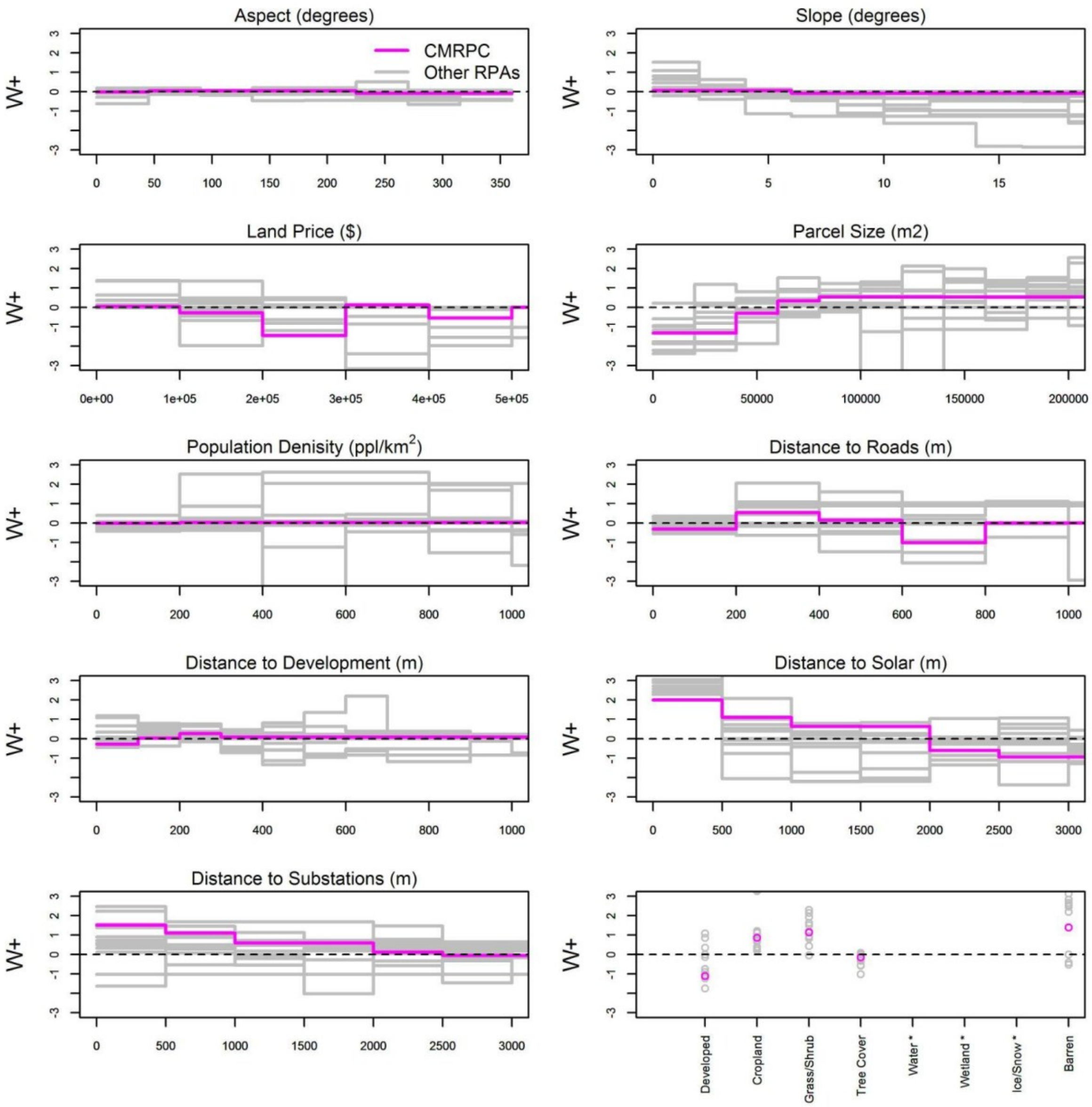

Figure A3. *Weights of Evidence for solar siting. Weights were calculated for each Regional Planning Area (RPA). Here, the Central Massachusetts Regional Planning Commission (CMRPC) is highlighted in pink. The CMRPC contained the highest rates of greenfield solar development in all scenarios.*

Appendix VI: Forest Adaptive Capacity and Resilience to Climate Change – Methodological Details

Forest Structure Classification

A variety of algorithms exist that could be used to classify the biomass reported by the LANDIS-II/PnET model. Because of time and resource constraints, an "off-the-shelf" solution was used. Most of the available, regionally relevant algorithms worked on forest inventory data (e.g., the sizes and other characteristics of trees tallied on sample plots), rather than estimates of biomass by species and age class. Thus, the FIA plot data (minus data for the tree species reported to be excluded from the study) used to initialize the landscape was run through the various algorithms to classify the plot in to a structural class. Complicating this approach was the fact that several species that were reported to have been excluded from the model, were observed to be included in the data. Next, a predictive model was built relating the patterns of biomass by age class (using the plot site tree data, converting site index from the site species to the tallied tree species, and the selected species-specific site curves to estimate tallied tree age from height) to the structural class. In this way, at each time step, the model output of biomass by age class within each pixel could be used to predict structural class.

The algorithms were as follows:

- **NED:** Embedded in the US Forest Service's Northeast Decision Model software is an algorithm that uses the stand medial diameter (calculated on page 385 GTR-NRS-86, Twery et al. 2012) to assign a structural class (page 381). This approach is consistent with classifications in DeGraaf et al. 2006.
- **FIA:** A combination of tree sizes and their relative stocking is used to assign a structural class (Arner et al. 2001, FIA National Core Field Guide (NRS) Volume I, 2024 and Burrill et al. 2024).
- **FVS:** The FVS Structural Class algorithm (Crookston and Stage, 1999) uses a combination of tree size, vertical foliage arrangement, and relative stocking in respective vertical canopy strata, to assign a structural class. The diameter threshold for large trees was set to 16 inches, consistent with other approaches used in New England (DeGraaf et al. 2006).
- **Supermajority:** Another model was proposed (called 'supermajority') by the research team that assigned a pixel to young or mature forest when more than 66% of the pixel biomass was less than 20 years old, or more than 120 years old, respectively. Because the initial community biomass age classes were 0-10, 10-25, 25-50, 50-75, 75-100, 100-125, 125-175, and 175+, the classification bins for forest structure were adjusted to less than 25 years old, and more than 125 years old.

Results from the different approaches are shown in Table A6 along with results from applying some of the same algorithms to different data sources representing Massachusetts' forests to illustrate the range of variability of estimates. State staff reviewed the available models and felt that the FVS algorithm was best suited for this project, as it relied on tree size and density, as well as the vertical and horizontal distribution of foliage. These combinations factors were viewed as more important indicators of forest structure and habitat characteristics than tree age or size or density alone, or combinations of two of those factors, as other algorithms use.

Table A6. *Proportion of forest area in structural classes, used by different forest structure classification algorithms, for different input datasets that provide estimates of current forest conditions. Input datasets include Initial Communities, used for this study; the most current available data from the USFS FIA program at the time of writing; and the TREEMAP dataset (Riley 2022). Classification algorithms include the Northeast Decision Model (NED, Twery et al. 2012, and DeGraaf et al 2006); FIA's stand size class algorithm (Arner et al. 2001, FIA National Core Field Guide (NRS) Volume I, 2024 and Burrill et al. 2024); FVS structural class model (Crookston and Stage, 1999); and the supermajority proposed early in this exercise whereby a pixel was classified as young or mature forest when 66% of its biomass was in modeled cohorts less than 20 or more than 125 years old, respectively.*

NED

Initial Communities: Class	% of area	FIA (2021): Class	% of area	TREEMAP: Class	% of area
Regeneration	0.1%				
Sapling	0.9%				
Poletimber	23.3%				
Small sawtimber	61.7%				
Large sawtimber	14.0%				

FIA

Initial Communities: Class	% of area	FIA (2021): Class	% of area	TREEMAP: Class	% of area
Bare ground	1.4%	Bare ground	0.6%	Bare ground	> 0.05%
Seedling/sapling	3.3%	Seedling/sapling	3.7%	Seedling/sapling	5.0%
Poletimber	20.4%	Poletimber	11.6%	Poletimber	25.9%
Sawtimber	75.0%	Sawtimber	84.0%	Sawtimber	69.1%

FVS

Initial Communities: Class	% of area	FIA (2021): Class	% of area	TREEMAP: Class	% of area
Bare ground	0.5%	Bare ground	> 0.05%	Bare ground	> 0.05%
Stand initiation	10.6%	Stand initiation	5.8%	Stand initiation	4.7%
Stem exclusion	48.4%	Stem exclusion	47.5%	Stem exclusion	63.1%
Understory reinitiation	13.0%	Understory reinitiation	15.6%	Understory reinitiation	9.9%
Young forest, multistrata	0.1%	Young forest, multistrata	0.0%	Young forest, multistrata	0.6%
Old forest, single strata	11.3%	Old forest, single strata	9.3%	Old forest, single strata	4.7%
Old forest, multistrata	16.1%	Old forest, multistrata	21.9%	Old forest, multistrata	16.9%

Supermajority

Initial Communities: Class	% of area	FIA (2021): Class	% of area	TREEMAP: Class	% of area
Young forest	1.6%				
'Middle age' forest	94.9%				
Mature forest	3.5%				

This algorithm uses the following classes:

- Bare ground (BG): Less than 5 percent crown cover and fewer than 200 trees per acre; areas shortly after regeneration before crown closure
- Stand initiation (SI): Less than 5 percent crown cover and greater than or equal to 200 trees per acre, or one stratum with a nominal diameter at breast height (dbh) less than 5 inches
- Stem exclusion (SE): One stratum with a nominal dbh between 5 and 16 inches unless the stand density index is below 30% of the maximum value for the stand
- Understory reinitiation (UR): Two strata with the uppermost having a dbh between 5 and 16 inches

- Young forest, multistrata (YM): Three or more strata with the uppermost having a dbh between 5 and 16 inches
- Old forest, single stratum (OS): One stratum, over 16 inches dbh, and smallest tree is greater than 3 inches dbh
- Old forest, multistratum (OM): Two or more strata, dbh of uppermost stratum is over 16 inches dbh; or one stratum, over 16 inches dbh, and smallest tree is less than or equal to 3 inches dbh

For each FIA plot in the initial communities dataset, the FVS classification model was applied, and the total above ground live tree biomass and proportion of that biomass in the different cohorts used to initialize the model were calculated. Those variables were then used as predictors in a classification model. Of particular note was the severe imbalance in observations, with plots classified as the stem exclusion structural stage representing 4-200 times more observations and 3-414 times more area than other stages. A variety of different classification models were evaluated, with the RUSBoost algorithm (Matlab 2023) providing reasonable results (confusion matrix Figure A4) given the imbalance in actual landscape structural conditions and in observations.

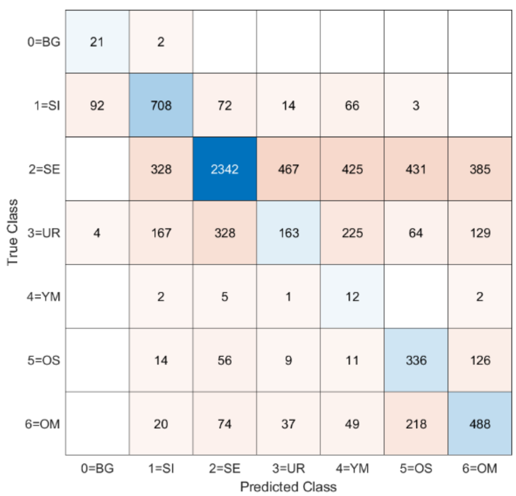

Figure A4. *Confusion matrix illustrating classification performance on validation data. True classes (i.e., results of applying FVS stand structure model to inventory data for each plot) are shown in rows, and predicted classes (i.e., results of predicting structural class based on biomass by modeled age cohort) are shown in columns. The diagonal cells show the correct prediction of classes. The number of observations in each combination of true and predicted classes are shown in each cell. Deeper shades of blue indicate a larger proportion of correct predictions; deeper shades of red indicate a larger proportion of incorrect predictions.*

Forest Composition

Table A7. *Management Priority Ratings*

Common name	Genus	Species	FIA SPCD	Management priority
balsam fir	Abies	balsamea	12	high
tamarack	Larix	laricina	71	high
black spruce	Picea	mariana	95	high
red spruce	Picea	rubens	97	high
red pine	Pinus	resinosa	125	low
pitch pine	Pinus	rigida	126	high
eastern white pine	Pinus	strobus	129	medium
eastern hemlock	Tsuga	canadensis	261	high
red maple	Acer	rubrum	316	low
sugar maple	Acer	saccharum	318	high
yellow birch	Betula	alleghaniensis	371	high
sweet birch	Betula	lenta	372	low
paper birch	Betula	papyrifera	375	high
gray birch	Betula	populifolia	379	medium
pignut hickory	Carya	glabra	403	high
American beech	Fagus	grandifolia	531	low
white ash	Fraxinus	americana	541	medium
black ash	Fraxinus	nigra	543	medium
hophornbeam	Ostrya	virginiana	701	medium
bigtooth aspen	Populus	grandidentata	743	medium
quaking aspen	Populus	tremuloides	746	high
black cherry	Prunus	serotina	762	high
white oak	Quercus	alba	802	high
scarlet oak	Quercus	coccinea	806	medium
chestnut oak	Quercus	prinus	832	high
northern red oak	Quercus	rubra	833	high
black oak	Quercus	velutina	837	medium
American basswood	Tilia	americana	951	medium
American elm	Ulmus	americana	972	medium

Appendix VII. Integrated Scenario Results

Table A8. *Mean annual carbon fluxes over 5-year timesteps from 2020 to 2100 for the eight Integrated Scenarios (with no development-driven land conversion) and two counterfactual scenario (with no harvesting and/or disturbance).*

		Mean annual carbon fluxes (MMTCO2e)					
Scenario	**Time-step**	*Growth*	*Mortality*	*Disturbance*	*Harvest*	*Salvage Harvest*	*Net Flux*
Counterfactual (no disturbance or harvest)	2020-2025	-7.79	1.08	0.00	0.00	0.00	-6.71
Counterfactual (no disturbance or harvest)	2025-2030	-6.18	0.98	0.00	0.00	0.00	-5.20
Counterfactual (no disturbance or harvest)	2030-2035	-7.72	1.10	0.00	0.00	0.00	-6.62
Counterfactual (no disturbance or harvest)	2035-2040	-7.19	1.08	0.00	0.00	0.00	-6.11
Counterfactual (no disturbance or harvest)	2040-2045	-6.21	1.17	0.00	0.00	0.00	-5.04
Counterfactual (no disturbance or harvest)	2045-2050	-7.54	1.52	0.00	0.00	0.00	-6.02
Counterfactual (no disturbance or harvest)	2050-2055	-6.74	1.56	0.00	0.00	0.00	-5.18
Counterfactual (no disturbance or harvest)	2055-2060	-5.86	2.07	0.00	0.00	0.00	-3.79
Counterfactual (no disturbance or harvest)	2060-2065	-4.94	2.45	0.00	0.00	0.00	-2.49
Counterfactual (no disturbance or harvest)	2065-2070	-4.83	2.97	0.00	0.00	0.00	-1.86
Counterfactual (no disturbance or harvest)	2070-2075	-5.68	3.11	0.00	0.00	0.00	-2.57
Counterfactual (no disturbance or harvest)	2075-2080	-5.34	3.13	0.00	0.00	0.00	-2.21
Counterfactual (no disturbance or harvest)	2080-2085	-4.34	3.10	0.00	0.00	0.00	-1.24
Counterfactual (no disturbance or harvest)	2085-2090	-5.74	3.56	0.00	0.00	0.00	-2.18
Counterfactual (no disturbance or harvest)	2090-2095	-3.50	3.38	0.00	0.00	0.00	-0.12
Counterfactual (no disturbance or harvest)	2095-2100	-3.43	4.08	0.00	0.00	0.00	0.65
Counterfactual + Low Disturbance + No Dev/Harv	2020-2025	-7.99	1.08	0.08	0.00	0.00	-6.83
Counterfactual + Low Disturbance + No Dev/Harv	2025-2030	-6.46	0.95	0.60	0.00	0.00	-4.91
Counterfactual + Low Disturbance + No Dev/Harv	2030-2035	-8.18	1.02	0.50	0.00	0.00	-6.66
Counterfactual + Low Disturbance + No Dev/Harv	2035-2040	-7.72	0.97	0.69	0.00	0.00	-6.06

Counterfactual + Low Disturbance + No Dev/Harv	2040-2045	-6.72	1.03	0.87	0.00	0.00	-4.82
Counterfactual + Low Disturbance + No Dev/Harv	2045-2050	-8.19	1.31	0.75	0.00	0.00	-6.13
Counterfactual + Low Disturbance + No Dev/Harv	2050-2055	-7.49	1.36	1.01	0.00	0.00	-5.12
Counterfactual + Low Disturbance + No Dev/Harv	2055-2060	-6.50	1.76	1.20	0.00	0.00	-3.54
Counterfactual + Low Disturbance + No Dev/Harv	2060-2065	-5.82	2.11	1.08	0.00	0.00	-2.63
Counterfactual + Low Disturbance + No Dev/Harv	2065-2070	-5.69	2.50	2.14	0.00	0.00	-1.06
Counterfactual + Low Disturbance + No Dev/Harv	2070-2075	-6.81	2.58	1.39	0.00	0.00	-2.83
Counterfactual + Low Disturbance + No Dev/Harv	2075-2080	-6.79	2.57	2.22	0.00	0.00	-2.00
Counterfactual + Low Disturbance + No Dev/Harv	2080-2085	-5.64	2.47	2.69	0.00	0.00	-0.47
Counterfactual + Low Disturbance + No Dev/Harv	2085-2090	-7.12	2.82	2.17	0.00	0.00	-2.14
Counterfactual + Low Disturbance + No Dev/Harv	2090-2095	-4.57	2.72	2.00	0.00	0.00	0.15
Counterfactual + Low Disturbance + No Dev/Harv	2095-2100	-4.64	3.38	1.78	0.00	0.00	0.52
Recent Trend Harvest + Low Disturbance	2020-2025	-8.38	1.95	0.07	0.70	0.00	-5.68
Recent Trend Harvest + Low Disturbance	2025-2030	-7.18	1.96	0.54	0.89	0.00	-3.85
Recent Trend Harvest + Low Disturbance	2030-2035	-9.01	1.58	0.43	1.02	0.00	-6.08
Recent Trend Harvest + Low Disturbance	2035-2040	-8.92	1.32	0.62	1.10	0.00	-6.04
Recent Trend Harvest + Low Disturbance	2040-2045	-8.01	1.37	0.77	1.17	0.00	-4.95
Recent Trend Harvest + Low Disturbance	2045-2050	-9.50	1.48	0.66	1.29	0.00	-6.41
Recent Trend Harvest + Low Disturbance	2050-2055	-9.05	1.49	0.90	1.39	0.00	-5.67
Recent Trend Harvest + Low Disturbance	2055-2060	-8.14	1.76	1.06	1.48	0.00	-4.25
Recent Trend Harvest + Low Disturbance	2060-2065	-7.54	2.01	0.95	1.51	0.00	-3.43
Recent Trend Harvest + Low Disturbance	2065-2070	-7.35	2.34	1.92	1.53	0.00	-1.89
Recent Trend Harvest + Low Disturbance	2070-2075	-8.58	2.36	1.25	1.59	0.00	-3.72
Recent Trend Harvest + Low Disturbance	2075-2080	-8.52	2.36	1.98	1.62	0.00	-2.87
Recent Trend Harvest + Low Disturbance	2080-2085	-7.42	2.25	2.42	1.65	0.00	-1.35

Recent Trend Harvest + Low Disturbance	2085-2090	-9.06	2.52	1.95	1.69	0.00	-3.22
Recent Trend Harvest + Low Disturbance	2090-2095	-6.36	2.46	1.79	1.72	0.00	-0.59
Recent Trend Harvest + Low Disturbance	2095-2100	-6.46	2.98	1.60	1.72	0.00	-0.36
Reserve Emphasis + Low Disturbance	2020-2025	-8.53	1.97	0.07	0.63	0.00	-5.89
Reserve Emphasis + Low Disturbance	2025-2030	-7.33	1.98	0.54	0.79	0.00	-4.08
Reserve Emphasis + Low Disturbance	2030-2035	-9.17	1.61	0.44	0.90	0.00	-6.32
Reserve Emphasis + Low Disturbance	2035-2040	-8.84	1.37	0.62	0.96	0.00	-6.06
Reserve Emphasis + Low Disturbance	2040-2045	-7.95	1.31	0.79	0.99	0.00	-5.10
Reserve Emphasis + Low Disturbance	2045-2050	-9.38	1.50	0.67	1.03	0.00	-6.52
Reserve Emphasis + Low Disturbance	2050-2055	-8.89	1.53	0.91	1.09	0.00	-5.75
Reserve Emphasis + Low Disturbance	2055-2060	-7.92	1.83	1.09	1.12	0.00	-4.30
Reserve Emphasis + Low Disturbance	2060-2065	-7.16	2.08	0.98	1.13	0.00	-3.35
Reserve Emphasis + Low Disturbance	2065-2070	-6.99	2.35	1.96	1.10	0.00	-1.91
Reserve Emphasis + Low Disturbance	2070-2075	-8.22	2.40	1.28	1.07	0.00	-3.80
Reserve Emphasis + Low Disturbance	2075-2080	-8.12	2.39	2.05	1.07	0.00	-2.93
Reserve Emphasis + Low Disturbance	2080-2085	-6.91	2.28	2.49	1.08	0.00	-1.32
Reserve Emphasis + Low Disturbance	2085-2090	-8.46	2.54	2.02	1.06	0.00	-3.18
Reserve Emphasis + Low Disturbance	2090-2095	-5.68	2.47	1.86	1.03	0.00	-0.52
Reserve Emphasis + Low Disturbance	2095-2100	-5.69	2.97	1.66	1.01	0.00	-0.25
Local Wood Emphasis + Low Disturbance	2020-2025	-8.68	2.08	0.07	1.84	0.00	-4.73
Local Wood Emphasis + Low Disturbance	2025-2030	-7.79	2.13	0.52	2.36	0.00	-2.83
Local Wood Emphasis + Low Disturbance	2030-2035	-9.79	1.79	0.41	2.72	0.00	-4.97
Local Wood Emphasis + Low Disturbance	2035-2040	-9.84	1.57	0.56	2.76	0.00	-5.11
Local Wood Emphasis + Low Disturbance	2040-2045	-9.30	1.48	0.69	2.58	0.00	-4.79
Local Wood Emphasis + Low Disturbance	2045-2050	-10.73	1.50	0.59	2.64	0.00	-6.34

Local Wood Emphasis + Low Disturbance	2050-2055	-10.39	1.48	0.80	2.83	0.00	-5.67
Local Wood Emphasis + Low Disturbance	2055-2060	-9.61	1.67	0.93	3.05	0.00	-4.37
Local Wood Emphasis + Low Disturbance	2060-2065	-8.88	1.84	0.84	3.16	0.00	-3.41
Local Wood Emphasis + Low Disturbance	2065-2070	-8.80	2.02	1.67	3.05	0.00	-2.39
Local Wood Emphasis + Low Disturbance	2070-2075	-10.15	2.03	1.09	3.01	0.00	-4.36
Local Wood Emphasis + Low Disturbance	2075-2080	-10.01	2.02	1.72	2.94	0.00	-3.65
Local Wood Emphasis + Low Disturbance	2080-2085	-8.83	1.93	2.11	2.92	0.00	-2.12
Local Wood Emphasis + Low Disturbance	2085-2090	-10.47	2.13	1.71	2.88	0.00	-4.08
Local Wood Emphasis + Low Disturbance	2090-2095	-7.73	2.08	1.58	2.82	0.00	-1.45
Local Wood Emphasis + Low Disturbance	2095-2100	-7.64	2.47	1.40	2.91	0.00	-1.06
Combined Emphasis + Low Disturbance	2020-2025	-8.59	2.05	0.07	1.39	0.00	-5.11
Combined Emphasis + Low Disturbance	2025-2030	-7.57	2.08	0.52	1.78	0.00	-3.24
Combined Emphasis + Low Disturbance	2030-2035	-9.53	1.74	0.43	2.07	0.00	-5.39
Combined Emphasis + Low Disturbance	2035-2040	-9.48	1.53	0.58	2.18	0.00	-5.35
Combined Emphasis + Low Disturbance	2040-2045	-8.88	1.46	0.72	2.20	0.00	-4.74
Combined Emphasis + Low Disturbance	2045-2050	-10.34	1.53	0.61	2.25	0.00	-6.29
Combined Emphasis + Low Disturbance	2050-2055	-9.96	1.52	0.83	2.33	0.00	-5.68
Combined Emphasis + Low Disturbance	2055-2060	-9.11	1.72	0.98	2.41	0.00	-4.40
Combined Emphasis + Low Disturbance	2060-2065	-8.35	1.90	0.87	2.50	0.00	-3.44
Combined Emphasis + Low Disturbance	2065-2070	-8.25	2.11	1.75	2.47	0.00	-2.24
Combined Emphasis + Low Disturbance	2070-2075	-9.57	2.14	1.15	2.47	0.00	-4.15
Combined Emphasis + Low Disturbance	2075-2080	-9.46	2.13	1.81	2.44	0.00	-3.39
Combined Emphasis + Low Disturbance	2080-2085	-8.30	2.03	2.23	2.41	0.00	-1.89
Combined Emphasis + Low Disturbance	2085-2090	-9.91	2.24	1.80	2.37	0.00	-3.83
Combined Emphasis + Low Disturbance	2090-2095	-7.15	2.17	1.65	2.33	0.00	-1.19

Combined Emphasis + Low Disturbance	2095-2100	-7.09	2.60	1.48	2.37	0.00	-0.84
Recent Trend Harvest + High Disturbance	2020-2025	-8.38	1.96	0.07	0.68	0.00	-5.68
Recent Trend Harvest + High Disturbance	2025-2030	-7.18	1.97	0.62	0.86	0.00	-3.75
Recent Trend Harvest + High Disturbance	2030-2035	-9.01	1.59	0.55	0.97	0.00	-5.93
Recent Trend Harvest + High Disturbance	2035-2040	-11.30	1.34	0.87	0.88	1.29	-6.97
Recent Trend Harvest + High Disturbance	2040-2045	-12.21	1.14	6.61	0.58	7.96	4.00
Recent Trend Harvest + High Disturbance	2045-2050	-13.75	0.91	7.57	0.51	2.44	-2.44
Recent Trend Harvest + High Disturbance	2050-2055	-13.87	0.80	5.67	0.47	1.56	-5.50
Recent Trend Harvest + High Disturbance	2055-2060	-12.55	0.77	10.66	0.42	4.92	4.09
Recent Trend Harvest + High Disturbance	2060-2065	-12.71	0.65	8.75	0.40	1.27	-1.76
Recent Trend Harvest + High Disturbance	2065-2070	-13.27	0.63	8.35	0.38	0.59	-3.41
Recent Trend Harvest + High Disturbance	2070-2075	-14.31	0.62	7.31	0.38	0.39	-5.70
Recent Trend Harvest + High Disturbance	2075-2080	-13.53	0.70	6.94	0.39	0.29	-5.29
Recent Trend Harvest + High Disturbance	2080-2085	-12.46	0.82	7.00	0.38	0.22	-4.11
Recent Trend Harvest + High Disturbance	2085-2090	-14.66	1.07	9.45	0.39	0.19	-3.64
Recent Trend Harvest + High Disturbance	2090-2095	-13.30	0.98	6.69	0.40	0.37	-4.91
Recent Trend Harvest + High Disturbance	2095-2100	-11.83	0.96	9.75	0.39	1.44	0.66
Reserve Emphasis + High Disturbance	2020-2025	-8.51	1.97	0.07	0.62	0.00	-5.86
Reserve Emphasis + High Disturbance	2025-2030	-7.31	1.98	0.62	0.79	0.00	-3.93
Reserve Emphasis + High Disturbance	2030-2035	-9.15	1.61	0.55	0.90	0.00	-6.13
Reserve Emphasis + High Disturbance	2035-2040	-11.30	1.37	0.88	0.87	0.89	-7.35
Reserve Emphasis + High Disturbance	2040-2045	-12.08	1.13	9.33	0.66	5.51	4.47
Reserve Emphasis + High Disturbance	2045-2050	-13.48	0.93	8.58	0.62	1.65	-1.80
Reserve Emphasis + High Disturbance	2050-2055	-13.46	0.83	6.15	0.61	1.01	-4.99
Reserve Emphasis + High Disturbance	2055-2060	-12.02	0.79	12.57	0.54	3.05	4.81

Reserve Emphasis + High Disturbance	2060-2065	-12.17	0.70	9.32	0.54	0.80	-0.92
Reserve Emphasis + High Disturbance	2065-2070	-12.81	0.67	8.67	0.54	0.37	-2.66
Reserve Emphasis + High Disturbance	2070-2075	-13.94	0.66	7.52	0.56	0.25	-5.05
Reserve Emphasis + High Disturbance	2075-2080	-13.33	0.73	7.05	0.58	0.18	-4.87
Reserve Emphasis + High Disturbance	2080-2085	-12.35	0.85	7.02	0.62	0.15	-3.77
Reserve Emphasis + High Disturbance	2085-2090	-14.49	1.05	9.23	0.63	0.12	-3.55
Reserve Emphasis + High Disturbance	2090-2095	-13.07	0.98	6.58	0.63	0.23	-4.70
Reserve Emphasis + High Disturbance	2095-2100	-11.77	0.96	9.91	0.62	0.86	0.54
Local Wood Emphasis + High Disturbance	2020-2025	-8.68	2.08	0.07	1.84	0.00	-4.70
Local Wood Emphasis + High Disturbance	2025-2030	-7.78	2.13	0.59	2.36	0.00	-2.73
Local Wood Emphasis + High Disturbance	2030-2035	-9.77	1.79	0.51	2.70	0.00	-4.80
Local Wood Emphasis + High Disturbance	2035-2040	-11.15	1.56	0.79	2.52	1.13	-5.20
Local Wood Emphasis + High Disturbance	2040-2045	-11.37	1.30	5.88	1.81	6.94	4.49
Local Wood Emphasis + High Disturbance	2045-2050	-12.67	1.06	6.60	1.63	2.10	-1.39
Local Wood Emphasis + High Disturbance	2050-2055	-12.58	0.95	4.93	1.59	1.32	-3.91
Local Wood Emphasis + High Disturbance	2055-2060	-10.91	0.89	8.95	1.42	4.04	4.27
Local Wood Emphasis + High Disturbance	2060-2065	-11.02	0.79	7.24	1.44	1.06	-0.61
Local Wood Emphasis + High Disturbance	2065-2070	-11.85	0.76	6.91	1.44	0.49	-2.34
Local Wood Emphasis + High Disturbance	2070-2075	-13.23	0.75	5.99	1.50	0.33	-4.75
Local Wood Emphasis + High Disturbance	2075-2080	-13.02	0.79	5.64	1.59	0.24	-4.85
Local Wood Emphasis + High Disturbance	2080-2085	-12.34	0.86	5.65	1.71	0.20	-3.99
Local Wood Emphasis + High Disturbance	2085-2090	-14.30	1.01	7.44	1.76	0.15	-4.03
Local Wood Emphasis + High Disturbance	2090-2095	-12.76	0.94	5.31	1.75	0.29	-4.52
Local Wood Emphasis + High Disturbance	2095-2100	-11.89	0.94	7.67	1.79	1.07	-0.46
Combined Emphasis + High Disturbance	2020-2025	-8.59	2.05	0.07	1.39	0.00	-5.09

Combined Emphasis + High Disturbance	2025-2030	-7.58	2.09	0.60	1.78	0.00	-3.12
Combined Emphasis + High Disturbance	2030-2035	-9.52	1.74	0.52	2.06	0.00	-5.24
Combined Emphasis + High Disturbance	2035-2040	-11.16	1.52	0.82	1.97	1.00	-5.90
Combined Emphasis + High Disturbance	2040-2045	-11.50	1.27	7.29	1.49	6.15	4.62
Combined Emphasis + High Disturbance	2045-2050	-12.82	1.03	7.34	1.34	1.84	-1.37
Combined Emphasis + High Disturbance	2050-2055	-12.75	0.93	5.37	1.28	1.14	-4.16
Combined Emphasis + High Disturbance	2055-2060	-11.17	0.87	10.31	1.12	3.46	4.46
Combined Emphasis + High Disturbance	2060-2065	-11.30	0.77	7.94	1.12	0.91	-0.67
Combined Emphasis + High Disturbance	2065-2070	-12.03	0.73	7.49	1.14	0.43	-2.34
Combined Emphasis + High Disturbance	2070-2075	-13.31	0.73	6.50	1.22	0.28	-4.68
Combined Emphasis + High Disturbance	2075-2080	-12.99	0.79	6.08	1.31	0.21	-4.67
Combined Emphasis + High Disturbance	2080-2085	-12.26	0.87	6.08	1.40	0.17	-3.81
Combined Emphasis + High Disturbance	2085-2090	-14.26	1.03	7.95	1.45	0.13	-3.79
Combined Emphasis + High Disturbance	2090-2095	-12.75	0.96	5.68	1.44	0.25	-4.46
Combined Emphasis + High Disturbance	2095-2100	-11.79	0.95	8.38	1.45	0.90	-0.14

Appendix VIII: Forest Resiliency – Additional Results

Case Study 1: Pitch Pine in Eastern Massachusetts

This community was defined as areas within the eastern group of ecological subsections used for this exercise with pitch pine comprising at least one third of above ground live tree biomass. Pitch pine is a species that is not expected to fare especially well under climate change (cite tree climate change atlas), but which is a species associated with critical natural communities. The type of management generally recommended for pine barrens (lower tree densities maintained by frequent, low-intensity disturbance) was not modeled and the full carbon benefits (e.g., high soil carbon stocks) of managing for these communities could not be realized due to the study constraint. Results are shown in Table A9. The composition of younger cohorts (0-10 and 10-25 years old) and older cohorts combined (25-999 years old) generally showed more favorable responses in the areas that were harvested. The proportion of biomass in the younger cohorts in pitch pine tended to not decline as sharply and, in some cases, increased.

Table A9. *Comparison of selected climate change adaptation and resiliency related metrics for pitch pine communities in eastern Massachusetts, focusing on the proportion of above ground live tree biomass in pitch pine for specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Percent biomass in pitch pine, 0-10 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 1	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,225	1,925	9,607	6,483	1,018	2,835	8,608	5,945	47,669	35,161	12,422	19,147	34,981	34,327	12,252	18,941
Pre-treatment	5.8%	13.5%	11.5%	13.6%	6.6%	17.8%	11.3%	12.7%	4.8%	4.7%	4.6%	5.0%	4.8%	4.7%	4.6%	5.0%
Post-treatment	8.5%	11.7%	10.6%	10.9%	8.5%	13.9%	11.1%	11.2%	5.5%	5.4%	5.5%	5.7%	5.6%	5.4%	5.9%	5.5%
Post-10 yr	4.0%	11.0%	11.3%	12.1%	5.1%	7.6%	11.2%	11.1%	2.1%	1.7%	2.0%	1.4%	2.0%	1.7%	1.8%	1.6%
Post-30 yr	50.4%	54.4%	56.1%	56.2%	0.2%	5.4%	8.4%	8.1%	38.1%	36.9%	36.2%	36.4%	0.4%	0.4%	0.6%	0.5%
Post-55 yr	4.7%	6.6%	7.2%	8.7%	0.9%	1.5%	4.1%	4.1%	2.4%	2.2%	2.5%	2.5%	0.4%	0.4%	0.3%	0.4%
Post-75 yr	1.5%	3.4%	5.3%	4.8%	0.2%	3.2%	3.0%	3.2%	1.5%	1.3%	1.7%	1.4%	0.6%	0.7%	0.5%	0.8%

Percent biomass in pitch pine, 10-25 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 2	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,225	1,925	9,607	6,483	1,018	2,835	8,608	5,945	47,669	35,161	12,422	19,147	34,981	34,327	12,252	18,941
Pre-treatment	15.2%	20.0%	14.9%	13.8%	12.6%	16.5%	12.0%	11.4%	8.7%	5.4%	7.4%	6.7%	9.4%	5.3%	7.3%	6.6%
Post-treatment	15.2%	18.4%	15.3%	15.8%	14.0%	18.8%	12.6%	11.5%	9.6%	6.4%	8.2%	7.6%	10.3%	6.2%	8.3%	7.5%
Post-10 yr	7.9%	12.4%	11.8%	11.6%	7.6%	14.6%	11.2%	12.3%	5.6%	5.3%	5.6%	5.4%	5.7%	5.2%	5.6%	5.2%
Post-30 yr	23.1%	33.8%	25.6%	27.7%	2.2%	6.0%	6.5%	6.3%	15.3%	12.1%	13.6%	12.0%	0.3%	0.3%	0.2%	0.3%
Post-55 yr	10.2%	9.8%	9.5%	10.4%	0.0%	2.7%	4.1%	3.2%	4.6%	4.6%	4.0%	4.3%	0.1%	0.1%	0.1%	0.1%
Post-75 yr	17.2%	27.4%	20.3%	21.8%	0.0%	1.4%	1.6%	2.7%	8.5%	6.0%	7.3%	6.0%	0.0%	0.0%	0.1%	0.1%

Percent biomass in pitch pine, 025-999 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 3	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,225	1,925	9,607	6,483	1,018	2,835	8,608	5,945	47,669	35,161	12,422	19,147	34,981	34,327	12,252	18,941
Pre-treatment	64.4%	62.7%	61.1%	60.6%	64.5%	60.3%	60.8%	60.8%	68.3%	66.5%	65.4%	65.1%	68.3%	66.5%	65.4%	65.1%
Post-treatment	64.6%	72.1%	75.2%	73.8%	64.5%	69.3%	74.6%	74.9%	68.1%	66.1%	65.3%	64.7%	68.1%	66.1%	65.3%	64.7%
Post-10 yr	63.6%	74.8%	75.8%	75.1%	62.5%	71.1%	75.7%	76.2%	66.4%	63.7%	63.8%	62.3%	66.3%	63.6%	63.8%	62.2%
Post-30 yr	22.5%	27.5%	23.6%	23.1%	61.7%	76.0%	77.8%	77.7%	20.4%	15.0%	17.8%	14.5%	65.7%	62.1%	62.4%	60.6%
Post-55 yr	30.3%	44.8%	39.5%	42.2%	59.7%	77.5%	74.7%	74.9%	28.1%	21.2%	25.3%	21.6%	62.6%	56.5%	57.7%	55.1%
Post-75 yr	18.1%	29.9%	28.6%	31.9%	55.2%	73.1%	66.4%	68.5%	17.6%	12.9%	15.6%	13.0%	56.3%	48.4%	50.2%	47.8%

The biomass in older cohorts showed a similar response. The composition of older cohorts remained more strongly dominated by pitch pine in the scenarios with low disturbance overall. In the high-disturbance scenarios, harvesting in general afforded some benefits, while scenarios employing the CSF/COF as modeled showed greater regeneration and retention of pitch pine despite a less favorable projected adaptability to climate change. However, management specific to communities with pitch pine have been employed for some time, so it is disingenuous to say that a shift to employing CSF/COF unambiguously affords benefits. This reinforces the role of silviculture in maintaining the resilience of this community's structure and function.

Case Study 2: Oak-Hickory Communities in Central Massachusetts

This community was defined as areas within the central group of ecological subsections used for this exercise with oak species comprising at least one third of above ground live tree biomass and hickory comprising at least 10% of above ground live tree biomass. These communities are important because the sites on which they occur and structure lend themselves to diverse plant communities, and the trees themselves are an important source of mast for wildlife. Oak is a considerable timber resource. These communities are also threatened by invasives and mesophication; to the extent that they are expected to expand under climate change, the presence and dominance of key tree species – oak and hickory – are important.

Results are shown in Table A10. The dominance of oak and hickory species in younger cohorts (0-10 and 10-25 years old) is generally greater in high-disturbance scenarios than low-disturbance scenarios. Areas that have been treated show much more favorable responses, consistently increasing in the proportion of oak and hickory in the 0-10 year old cohort, while unmanaged areas show much smaller gains in high-disturbance scenarios and losses in low-disturbance scenarios. With respect to older cohorts of oak and hickory species (25 years and older), untreated areas consistently showed small declines in dominance of those species whereas, in scenarios employing modeled CSF/COF, treated areas showed consistent increases in the proportion of oak and hickory biomass in older cohorts. Scenarios employing modeled recent trend silviculture showed virtually no change in the proportion of oak and hickory biomass in the older cohorts.

Table A10. *Comparison of selected climate change adaptation and resiliency related metrics for oak-hickory communities in central Massachusetts, focusing on the proportion of above ground live tree biomass in both oak and hickory species for specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Percent biomass in oak - hickory species, 0-10 years

	Treated area Scenario								Untreated area Scenario							
Subtable 1	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	21.9%	32.4%	27.3%	30.7%	19.6%	25.9%	25.1%	29.9%	10.0%	11.2%	9.2%	9.9%	8.9%	11.3%	9.0%	10.1%
Post-treatment	26.6%	33.5%	34.5%	31.5%	25.9%	31.9%	30.5%	30.8%	12.7%	13.8%	11.9%	13.0%	11.9%	14.2%	11.7%	12.8%
Post-10 yr	20.2%	35.2%	39.1%	40.0%	16.4%	34.2%	36.4%	38.7%	6.8%	6.7%	6.5%	6.8%	6.3%	6.9%	5.8%	7.2%
Post-30 yr	36.7%	38.5%	36.3%	39.7%	10.5%	29.6%	31.0%	32.9%	20.7%	19.8%	20.6%	21.1%	4.4%	4.1%	4.3%	4.1%
Post-55 yr	33.4%	37.4%	37.3%	41.1%	19.0%	32.1%	38.2%	34.2%	16.2%	14.6%	18.0%	16.4%	6.6%	5.5%	6.4%	6.1%
Post-75 yr	26.9%	43.2%	39.2%	42.1%	13.8%	39.8%	35.9%	37.1%	13.5%	13.2%	14.9%	14.4%	9.0%	6.5%	9.1%	8.5%

Percent biomass in oak-hickory species, 10-25 years

	Treated area Scenario								Untreated area Scenario							
Subtable 2	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	1.0%	1.0%	0.4%	0.9%	1.5%	0.9%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Post-treatment	7.1%	12.8%	14.3%	15.8%	5.8%	10.9%	9.7%	10.2%	3.1%	3.6%	2.9%	3.2%	2.8%	3.6%	2.8%	3.2%
Post-10 yr	34.2%	38.5%	39.6%	37.6%	29.2%	37.9%	33.9%	35.1%	15.5%	17.2%	14.7%	15.9%	14.3%	17.5%	14.5%	15.7%
Post-30 yr	50.5%	53.8%	54.9%	63.4%	27.3%	50.5%	50.2%	49.7%	36.8%	34.4%	34.7%	35.1%	10.2%	10.2%	9.5%	10.0%
Post-55 yr	45.6%	47.2%	46.4%	40.9%	18.1%	38.7%	50.9%	48.2%	35.9%	35.1%	37.0%	36.2%	7.0%	5.8%	7.1%	6.8%
Post-75 yr	37.5%	41.6%	47.0%	54.4%	22.4%	38.0%	49.5%	42.9%	20.3%	19.2%	21.7%	20.9%	8.8%	7.7%	9.3%	8.6%

Percent biomass in oak-hickory species, 025-999 years

	Treated area Scenario								Untreated area Scenario							
Subtable 3	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	76.2%	73.6%	74.1%	74.4%	76.2%	74.0%	74.3%	72.6%	82.1%	82.1%	82.1%	82.3%	82.2%	82.1%	82.2%	82.3%
Post-treatment	76.0%	75.6%	78.7%	77.9%	76.2%	77.3%	78.1%	76.8%	82.0%	82.0%	82.1%	82.2%	82.3%	82.0%	82.2%	82.2%
Post-10 yr	76.0%	75.3%	78.8%	77.9%	76.0%	77.5%	78.2%	76.7%	81.7%	81.5%	81.8%	81.8%	82.0%	81.5%	81.9%	81.8%
Post-30 yr	76.2%	77.3%	82.3%	79.1%	75.5%	77.6%	81.5%	78.9%	80.8%	80.4%	81.0%	80.8%	81.5%	80.7%	81.4%	81.2%
Post-55 yr	76.5%	78.2%	81.6%	81.6%	75.6%	79.0%	82.9%	80.3%	79.3%	78.2%	80.0%	79.2%	81.2%	80.0%	81.1%	80.8%
Post-75 yr	76.0%	79.2%	82.8%	82.2%	76.1%	80.4%	85.4%	81.4%	78.4%	77.0%	79.4%	78.4%	80.9%	79.3%	80.8%	80.3%

Only one hickory species of the several that occur in Massachusetts was modeled, and biomass from the non-modeled *Carya* spp. was not substituted into a surrogate, modeled species. Focusing on just the hickory component of this community (results in Table A11), scenarios employing modeled CSF/COF showed increases in the proportion of the youngest cohort's biomass (0-10 years) over the modeling period. Untreated areas in high disturbance regime scenarios showed increases as well, but smaller than treated areas. Untreated areas in low disturbance regime scenarios showed declines in the proportion of that cohort's biomass. In the next-oldest cohort (10-25 years), treated areas showed much greater increases in the proportion of hickory than untreated areas. Results for the oldest cohorts (25 years and older) showed increases in the proportion of hickory biomass in treated areas under all scenarios. In untreated areas, the high disturbance regime scenarios showed a change in hickory biomass of within 1% more or less than the starting proportion while the lower disturbance regime scenarios showed greater increases.

Table A11. *Comparison of selected climate change adaptation and resiliency related metrics for oak-hickory communities in central Massachusetts, focusing on the proportion of above ground live tree biomass in just hickory species for specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Percent biomass in hickory, 0-10 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 4	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	7.7%	6.7%	7.0%	7.6%	6.5%	4.8%	6.3%	7.7%	2.9%	3.2%	2.7%	2.8%	2.8%	3.2%	2.6%	2.8%
Post-treatment	8.3%	7.0%	9.4%	10.8%	6.4%	7.3%	10.2%	11.2%	3.6%	4.0%	3.3%	3.5%	3.7%	4.0%	3.3%	3.7%
Post-10 yr	5.3%	10.5%	8.9%	10.3%	5.8%	13.2%	9.6%	9.2%	1.9%	1.9%	1.5%	1.9%	1.6%	1.9%	1.5%	2.0%
Post-30 yr	9.2%	10.4%	12.1%	13.4%	5.4%	9.4%	5.6%	8.3%	5.8%	5.5%	6.2%	5.9%	1.3%	1.2%	1.3%	1.1%
Post-55 yr	9.8%	10.1%	11.2%	12.6%	4.9%	10.8%	12.0%	12.0%	4.6%	3.9%	5.0%	4.6%	1.9%	1.6%	1.9%	1.9%
Post-75 yr	6.7%	14.3%	8.8%	12.2%	3.1%	11.4%	10.6%	10.1%	3.8%	3.7%	4.2%	3.8%	2.5%	1.9%	2.3%	2.5%

Percent biomass in hickory, 10-25 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 5	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Post-treatment	1.9%	3.5%	4.7%	2.9%	2.1%	2.1%	1.4%	1.7%	0.8%	1.0%	0.9%	0.9%	0.8%	1.1%	0.9%	0.9%
Post-10 yr	10.4%	8.7%	10.7%	11.5%	8.8%	10.6%	10.5%	11.5%	4.3%	4.9%	4.3%	4.5%	4.3%	5.0%	4.2%	4.4%
Post-30 yr	13.8%	18.1%	16.8%	16.8%	8.8%	14.7%	14.7%	15.3%	10.1%	9.6%	9.5%	10.0%	3.4%	3.0%	3.2%	3.0%
Post-55 yr	10.6%	12.3%	12.1%	9.0%	5.1%	10.3%	14.1%	16.3%	10.1%	9.1%	10.5%	9.7%	2.1%	1.6%	2.2%	2.0%
Post-75 yr	11.1%	8.4%	12.2%	16.8%	6.0%	11.2%	14.0%	12.2%	5.9%	5.3%	6.1%	6.0%	2.4%	2.2%	2.5%	2.3%

Percent biomass in hickory species, 025-999 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 6	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	17.7%	18.1%	17.2%	18.0%	17.5%	17.9%	17.9%	17.5%	19.6%	18.6%	20.2%	19.7%	20.6%	18.5%	20.3%	19.7%
Post-treatment	17.7%	18.6%	16.3%	17.2%	17.4%	18.7%	17.4%	17.1%	19.7%	18.7%	20.3%	19.8%	20.7%	18.6%	20.3%	19.8%
Post-10 yr	17.3%	18.0%	15.9%	16.8%	17.0%	18.3%	17.1%	16.9%	19.6%	18.5%	20.0%	19.5%	20.5%	18.5%	20.1%	19.6%
Post-30 yr	17.4%	21.2%	15.9%	18.7%	17.2%	22.9%	17.8%	20.0%	19.0%	17.5%	19.5%	18.8%	21.6%	19.1%	21.0%	20.3%
Post-55 yr	18.5%	25.0%	18.2%	19.7%	20.4%	28.5%	22.0%	23.4%	19.7%	18.0%	20.5%	19.6%	25.6%	21.1%	24.4%	23.1%
Post-75 yr	19.3%	26.0%	18.1%	21.3%	23.0%	32.6%	21.3%	24.4%	19.9%	18.0%	20.5%	19.8%	30.9%	23.6%	29.2%	27.0%

All combinations of scenarios and treatment status showed declines in species diversity as measured by Simpson's D (a measure of how evenly or concentrated members of a population are within different classes or domains, Table A12). In high disturbance regime scenarios, declines were slightly proportionally greater in treated areas; in low disturbance regime scenarios, declines were slightly proportionally greater in untreated areas.

Table A12. *Comparison of selected climate change adaptation and resiliency related metrics for oak-hickory communities in central Massachusetts, focusing on species diversity as assessed by applying Simpson's diversity index (D) to the proportion of biomass in each species. Values range between 0 and 1, with values closer to 1 indicating biomass is more evenly distributed across a greater number of present species. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Species diversity (Simpson's D), all age classes

	Treated area Scenario								Untreated area Scenario							
Subtable 7	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	0.72	0.74	0.75	0.75	0.70	0.74	0.75	0.74	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Post-treatment	0.71	0.71	0.68	0.69	0.70	0.70	0.69	0.68	0.65	0.65	0.64	0.64	0.64	0.65	0.64	0.64
Post-10 yr	0.70	0.71	0.68	0.70	0.69	0.70	0.70	0.69	0.64	0.64	0.63	0.63	0.62	0.64	0.62	0.63
Post-30 yr	0.72	0.69	0.67	0.67	0.67	0.66	0.63	0.62	0.66	0.66	0.65	0.65	0.60	0.62	0.60	0.61
Post-55 yr	0.70	0.68	0.63	0.64	0.63	0.61	0.57	0.58	0.64	0.64	0.62	0.63	0.53	0.56	0.53	0.54
Post-75 yr	0.68	0.65	0.62	0.63	0.60	0.58	0.52	0.55	0.60	0.61	0.59	0.59	0.46	0.50	0.47	0.48

The number of different age classes represented (richness) is also an important indicator of resilience. Trees are susceptible to different stressors and damaging agents at different points in their life; having trees present of an appropriate number of different ages can help a site be more resilient, re-occupy vacated growing space more rapidly, and stabilize ecosystem service provision. The classes used for initializing the landscape were used for these purposes as well, since those defined the age class resolution of this exercise. In general, treated areas experienced greater increases in the average number of different age classes present than untreated areas within scenarios; and high disturbance regime scenarios experienced greater increases than low disturbance regime scenarios (Table A13). Unmanaged areas in low disturbance regime scenarios lost age class richness, as did areas treated with recent trends silviculture in low disturbance scenarios. Modeled recent trends silviculture offered among the greatest proportional gains in age class richness.

Considering the extent to which forests of this type in the central part of the Commonwealth provide ecosystem services such as clean drinking water, the provision of which depends in no small part on species and age class diversity, the benefits of silviculture, and CSF/COF, are evident.

Table A13. *Comparison of selected climate change adaptation and resiliency related metrics for oak-hickory communities in central Massachusetts, focusing on age class richness. Values represent the average number of age classes (using the initial communities cohorts) present. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Age class richness

	Treated area Scenario								Untreated area Scenario							
Subtable 8	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	1,075	1,123	2,699	2,569	806	1,253	3,061	2,273	26,425	23,955	11,371	14,840	13,535	23,937	11,301	14,795
Pre-treatment	4.2	4.9	4.8	4.9	3.8	4.7	4.8	4.9	2.9	2.8	2.9	2.8	2.9	2.8	2.9	2.8
Post-treatment	4.3	5.0	4.9	5.0	4.0	4.9	4.9	5.0	2.9	2.9	2.9	2.9	3.0	2.9	2.9	2.9
Post-10 yr	4.6	5.6	5.5	5.5	4.2	5.3	5.4	5.6	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Post-30 yr	5.2	5.8	5.6	5.8	4.2	5.4	5.6	5.7	3.7	3.7	3.6	3.6	2.9	2.9	2.9	2.9
Post-55 yr	5.3	6.0	5.8	5.8	4.0	5.4	5.7	5.8	3.9	3.9	3.9	3.9	2.5	2.5	2.5	2.5
Post-75 yr	5.2	5.9	5.8	6.0	3.6	5.0	5.4	5.6	3.6	3.6	3.6	3.6	2.2	2.1	2.2	2.2

Case Study 3: Spruce-Fir in Western Massachusetts

This community was defined as areas within the western group of ecological subsections used for this exercise with spruce and fir species comprising at least one third of above ground live tree biomass. These communities, already rare in Massachusetts, are especially vulnerable to climate change. They generally already occur at some of the locally highest elevations within the Commonwealth and so have little space to retreat to cooler temperatures as the climate warms. For these comparisons, it is important to note that relatively little area of this community was treated early in the model.

The proportion of biomass of the youngest cohort (0-10 years old, Table A14) in spruce and fir species consistently declined in untreated areas across all scenarios. Treated areas employing modeled recent trends silviculture also experienced declines, while treated areas with modeled CSF/COF experienced mixed results, sometimes showing decreases and in other cases showing large increases. Results tended to be similar for the next-oldest cohort; with the proportion of biomass in spruce and fir species declining consistently across untreated areas and showing variable results in treated areas. Within the oldest cohort (175 years and older), the proportion of biomass in spruce and fir species was more variable – expected given the small area harvested – but on average similar to untreated areas, with managed areas showing a greater increase.

Table A14. *Comparison of selected climate change adaptation and resiliency related metrics for spruce-fir communities in western Massachusetts, focusing on the proportion of above ground live tree biomass in both spruce and fir species for specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Percent biomass in spruce-fir, 0-10 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 1	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	198	50	134	74	240	26	102	50	14,105	15,116	8,272	12,025	10,448	15,104	8,276	11,997
Pre-treatment	19.4%	19.9%	13.9%	10.9%	20.9%	16.3%	14.7%	21.3%	14.3%	14.2%	14.1%	14.1%	13.5%	14.3%	13.7%	14.2%
Post-treatment	20.1%	12.8%	23.9%	19.2%	22.9%	45.3%	21.3%	16.0%	17.6%	18.5%	17.9%	17.6%	17.2%	17.7%	17.0%	18.1%
Post-10 yr	26.1%	17.0%	12.9%	30.3%	17.8%	0.0%	25.1%	13.4%	14.6%	13.9%	14.1%	13.8%	15.0%	14.8%	14.5%	14.3%
Post-30 yr	22.9%	21.4%	6.2%	14.2%	16.6%	12.1%	31.3%	35.7%	13.5%	12.5%	14.3%	13.0%	8.1%	7.7%	7.2%	7.8%
Post-55 yr	4.2%	5.9%	17.8%	13.2%	9.0%	12.7%	50.1%	20.0%	8.8%	8.5%	8.2%	9.0%	6.5%	5.7%	6.0%	5.8%
Post-75 yr	12.6%	23.5%	20.0%	7.9%	7.4%	26.4%	17.5%	9.4%	6.0%	6.1%	6.8%	6.4%	4.8%	4.4%	4.0%	4.5%

Percent biomass in spruce-fir, 10-25 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 2	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	198	50	134	74	240	26	102	50	14,105	15,116	8,272	12,025	10,448	15,104	8,276	11,997
Pre-treatment	17.3%	5.7%	23.7%	25.3%	18.9%	0.0%	13.9%	27.5%	15.1%	14.8%	13.6%	14.4%	15.3%	14.8%	13.7%	14.4%
Post-treatment	24.2%	17.7%	24.4%	35.6%	21.9%	0.0%	15.5%	38.0%	18.5%	18.0%	16.7%	17.5%	18.3%	18.0%	16.9%	17.7%
Post-10 yr	21.1%	19.3%	25.0%	24.7%	20.4%	42.0%	27.5%	17.6%	19.0%	19.4%	19.2%	18.8%	18.4%	18.9%	18.5%	19.2%
Post-30 yr	20.0%	32.8%	15.2%	11.6%	30.4%	18.0%	32.0%	12.4%	17.3%	17.4%	16.2%	16.9%	15.4%	15.0%	13.5%	15.1%
Post-55 yr	12.0%	19.8%	12.0%	16.8%	11.1%	11.7%	18.0%	26.0%	12.6%	12.9%	12.5%	12.8%	7.7%	7.6%	7.8%	7.5%
Post-75 yr	4.7%	10.8%	19.9%	7.3%	15.2%	31.2%	23.0%	7.2%	8.0%	7.5%	8.2%	8.1%	6.2%	5.9%	5.9%	5.9%

Percent biomass in spruce-fir, 175-999 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 3	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	198	50	134	74	240	26	102	50	14,105	15,116	8,272	12,025	10,448	15,104	8,276	11,997
Pre-treatment	14.9%	15.2%	14.6%	0.0%	12.7%	0.0%	10.7%	11.1%	7.4%	7.9%	7.7%	7.9%	7.4%	7.9%	7.6%	7.9%
Post-treatment	15.0%	15.4%	15.3%	0.0%	12.7%	0.0%	13.5%	11.1%	7.5%	8.1%	7.9%	8.1%	7.6%	8.0%	7.9%	8.1%
Post-10 yr	15.2%	15.2%	14.4%	0.0%	12.8%	0.0%	13.0%	11.1%	6.8%	7.2%	7.1%	7.2%	6.8%	7.3%	7.1%	7.3%
Post-30 yr	12.9%	16.0%	6.9%	0.0%	9.9%	0.0%	0.0%	11.1%	3.7%	3.9%	3.7%	3.7%	3.4%	3.8%	3.7%	3.7%
Post-55 yr	57.4%	31.9%	52.8%	47.0%	50.4%	67.1%	48.7%	49.4%	27.9%	31.0%	30.2%	29.6%	29.2%	33.6%	33.1%	32.5%
Post-75 yr	49.5%	29.6%	45.6%	43.4%	45.7%	68.7%	42.5%	62.5%	24.6%	29.3%	27.1%	27.1%	29.1%	33.4%	32.5%	32.0%

Again, an assessment of age class structure (Table A15) is an important for this community as well; but the number of different cohorts present is not the sole structural metric associated with resiliency for this forest type. Spruce-fir forests tend to be associated with uneven-age structure, but gaps and patches of a variety of sizes are necessary to retain the full assemblage of species and characteristics. Treated areas started with slightly higher age class richness, and consistently showed greater increases in age class richness. Untreated areas in low disturbance regime scenarios consistently experienced slight losses of age class richness.

Table A15. *Comparison of selected climate change adaptation and resiliency related metrics for spruce-fir communities in western Massachusetts, focusing on age class richness. Richness as defined as before, where values represent the average number of age classes (using the initial communities cohorts) present. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Age class richness																
	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 4	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	198	50	134	74	240	26	102	50	14,105	15,116	8,272	12,025	10,448	15,104	8,276	11,997
Pre-treatment	5.5	5.6	5.9	5.7	5.4	5.7	5.6	5.4	3.9	4.0	4.0	4.0	3.9	4.0	3.9	4.0
Post-treatment	5.7	5.9	6.0	6.0	5.7	5.3	5.7	5.4	4.1	4.2	4.2	4.2	4.1	4.2	4.2	4.2
Post-10 yr	6.0	6.6	6.4	6.4	6.1	6.2	6.4	5.8	4.5	4.5	4.5	4.5	4.4	4.5	4.5	4.5
Post-30 yr	6.3	6.4	6.0	6.5	6.0	6.2	6.4	6.1	4.8	4.8	4.8	4.8	4.4	4.4	4.4	4.4
Post-55 yr	6.6	6.8	6.2	6.9	5.9	6.0	6.4	6.4	4.9	4.9	4.9	4.9	4.1	4.2	4.1	4.2
Post-75 yr	6.4	7.0	6.0	6.7	5.6	6.7	6.4	6.7	4.6	4.6	4.7	4.6	3.8	3.9	3.8	3.9

Case Study 4: Beech-Birch-Maple in Western Massachusetts

This community was defined as areas within the western group of ecological subsections used for this exercise with American beech, yellow birch, and sugar maple species comprising at least one third of above ground live tree biomass. This is the classic northern hardwoods community and can occur along a gradient of succession with different species present at different times. Habitat for a wide range of species is present. These forests tend to prefer cooler and moister sites, so some amount of vulnerability to climate change is expected. Stressors like invasive plants and introduced pests and pathogens have and will continue to exert a strong influence on this natural community. Because of the wide range of associated successional species, a variety of disturbance types (medium patch through large openings are needed to regenerate and recruit them all.

The proportion of biomass in beech, birch, and maple in the youngest cohorts (0-25 years, Table A16) was initially slightly less in untreated areas. The proportion of biomass in those species in those cohorts experienced a greater mean proportional increase in treated areas, except the high-disturbance local wood emphasis scenario, which experienced a very slight decrease. This is likely explained by the much greater species richness treatments in this scenario exhibited. Generally, low disturbance regime scenarios exhibited greater increases than high disturbance regime scenarios in treated areas, and the proportion of biomass in beech, birch, and maple in those younger cohorts declined in untreated areas in low disturbance regime scenarios. In older cohorts (25 years and older), the proportion of biomass in beech, birch, and maple was initially greater in untreated areas. The high disturbance combined emphasis scenario also experiencing a slight decline in the proportion of biomass in beech, birch, and maple. Increases in the proportion of biomass in beech, birch, and maple were greater in low disturbance regime scenarios in general, and untreated areas in general. Increases in untreated areas are generally explained by increases in beech.

Table A16. *Comparison of selected climate change adaptation and resiliency related metrics for northern hardwoods communities in western Massachusetts, focusing on the proportion of above ground live biomass in beech, yellow birch, and sugar maple, within specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 1	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	23.2%	28.3%	31.9%	30.3%	26.1%	29.4%	29.9%	30.8%	14.7%	15.5%	15.9%	15.7%	16.2%	15.5%	15.9%	15.6%
Post-treatment	30.2%	31.4%	31.7%	31.9%	31.2%	30.0%	32.1%	32.8%	19.7%	20.4%	20.8%	20.4%	21.0%	20.3%	20.7%	20.5%
Post-10 yr	33.0%	34.2%	33.4%	33.5%	33.5%	33.9%	33.7%	34.2%	21.1%	21.0%	21.1%	21.2%	21.2%	20.9%	21.1%	20.9%
Post-30 yr	32.8%	31.7%	31.6%	32.9%	31.5%	36.2%	34.1%	35.3%	28.2%	25.4%	25.9%	25.3%	15.7%	15.3%	15.9%	15.5%
Post-55 yr	32.6%	30.6%	30.2%	31.6%	28.8%	37.0%	36.1%	36.8%	24.8%	22.4%	23.2%	22.6%	11.8%	11.4%	11.7%	11.5%
Post-75 yr	28.8%	32.5%	31.8%	32.1%	31.3%	38.4%	38.0%	37.6%	18.5%	18.0%	18.2%	17.7%	13.1%	12.6%	12.8%	13.0%

Percent biomass in beech-birch-maple, 25-999 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 2	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	53.4%	48.3%	48.0%	48.5%	53.3%	49.1%	48.2%	47.9%	65.3%	66.2%	67.2%	67.3%	67.2%	66.2%	67.1%	67.2%
Post-treatment	56.2%	51.6%	51.2%	52.2%	56.4%	52.5%	51.6%	51.4%	69.1%	69.7%	70.6%	70.7%	70.6%	69.7%	70.6%	70.7%
Post-10 yr	56.6%	50.9%	50.1%	51.0%	56.9%	51.7%	50.5%	50.4%	71.2%	71.8%	72.8%	72.8%	72.7%	71.8%	72.8%	72.8%
Post-30 yr	57.4%	52.6%	49.8%	51.0%	58.4%	51.4%	49.0%	48.7%	71.8%	73.1%	73.8%	73.9%	76.0%	75.2%	76.0%	76.0%
Post-55 yr	57.0%	49.3%	45.4%	46.6%	61.6%	53.3%	49.7%	49.5%	69.7%	72.4%	72.6%	72.9%	80.6%	79.9%	80.6%	80.6%
Post-75 yr	56.8%	48.4%	43.9%	45.2%	64.0%	55.8%	51.2%	51.7%	68.3%	71.3%	71.3%	71.7%	82.9%	82.2%	82.7%	82.7%

In these forests the proliferation of beech is a serious problem. Beech exhibits vigorous root sprouting, which can be exacerbated by browse and beech bark disease, a complex interaction between non-native and native pests and pathogens. It forms a dense under- and mid-story that can inhibit regeneration of other species. Silviculture has generally focused on controlling beech sprouting at the time of regeneration, and selecting for disease free and phenotypically-resistant trees during stand tending operations (e.g., Leak et al.). Beech leaf disease, a new novel disease that was not modeled in this exercise, may change the outlook, but modeling silviculture that tried to control beech and beech bark disease is an important part of silviculture and was modeled in CSF/COF prescriptions.

This is evident in the results of beech composition of the same two groups of cohorts as earlier. The proportion of beech biomass in trees under 25 years old (Table A17) increased in untreated areas in high disturbance regime scenarios, from 16-34% across all scenarios; whereas in treated areas it increased from 1-29%. In low disturbance regime scenarios, the proportion of biomass in beech in trees under 25 years old increased in treated areas, and decreased slightly in untreated areas. For beech in older cohorts over 25 years, the effects of stand tending and silviculture were evident. The high disturbance regime, local wood emphasis, and combined emphasis scenarios observed slight reductions in the proportion of beech biomass in cohorts over 25 years in treated areas. Treated areas in scenarios employing modeled recent trends silviculture observed greater proportional increases (79-122%) than treated areas using CSF/COF silviculture (-5-46%). Untreated areas exhibited proportional increases of 75-123% again.

Table A17. *Comparison of selected climate change adaptation and resiliency related metrics for northern hardwoods communities in western Massachusetts, focusing on the proportion of above ground live biomass in beech for specified cohorts. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Percent biomass in beech, 0-25 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 3	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	9.1%	11.8%	14.2%	12.5%	10.0%	12.6%	12.8%	13.0%	6.0%	6.5%	6.2%	6.4%	6.7%	6.5%	6.3%	6.4%
Post-treatment	11.8%	14.0%	17.7%	18.0%	12.5%	11.9%	17.9%	18.7%	7.8%	8.3%	8.0%	8.1%	8.4%	8.3%	8.0%	8.1%
Post-10 yr	12.6%	14.6%	16.0%	16.0%	12.3%	13.2%	15.7%	16.6%	7.7%	7.9%	7.6%	7.8%	7.7%	7.8%	7.7%	7.6%
Post-30 yr	13.4%	12.3%	14.3%	14.9%	11.9%	12.8%	15.2%	15.5%	10.4%	9.6%	9.9%	9.6%	6.1%	6.1%	6.1%	6.0%
Post-55 yr	13.7%	11.7%	12.8%	13.4%	12.0%	15.2%	15.6%	16.0%	10.2%	8.9%	9.1%	8.9%	5.1%	4.8%	4.8%	4.9%
Post-75 yr	11.8%	12.7%	14.3%	14.9%	14.3%	16.0%	18.3%	17.8%	8.0%	7.7%	7.7%	7.4%	6.2%	5.9%	6.0%	6.0%

Percent biomass in beech, 25-999 years

	Treated area								Untreated area							
	Scenario								Scenario							
Subtable 4	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	13.9%	10.9%	11.8%	11.9%	13.2%	11.0%	11.8%	11.9%	16.6%	18.2%	16.4%	16.5%	16.6%	18.2%	16.4%	16.5%
Post-treatment	14.6%	7.8%	6.3%	6.4%	13.9%	8.1%	6.2%	6.2%	17.9%	19.6%	17.6%	17.8%	17.9%	19.5%	17.6%	17.8%
Post-10 yr	15.9%	8.8%	6.9%	7.0%	15.3%	9.0%	6.9%	6.9%	19.9%	21.6%	19.5%	19.8%	19.8%	21.6%	19.6%	19.8%
Post-30 yr	16.5%	8.4%	6.8%	6.9%	18.4%	9.7%	7.8%	7.9%	20.2%	22.7%	20.5%	20.8%	24.2%	26.3%	23.8%	24.1%
Post-55 yr	20.9%	10.9%	8.8%	8.7%	24.0%	12.5%	10.7%	10.8%	24.8%	27.8%	25.3%	25.8%	31.0%	33.5%	30.6%	31.0%
Post-75 yr	24.8%	13.3%	11.3%	11.2%	29.4%	16.1%	14.9%	14.7%	29.0%	32.1%	29.6%	30.1%	36.7%	39.4%	36.3%	36.9%

Species richness and diversity are also important measures of community resilience. While beech, birch, and maple are defining members of this forest type, a large number of associates are important as well. These other species have a range of shade tolerance and regeneration niches, so providing a variety of conditions to facilitate that regeneration and recruitment is important. Species richness (Table A18) exhibited strong and persistent increases in treated areas in all scenarios (an average increase of 0.92 species) except the recent trends low disturbance scenario. It increased very slightly in untreated areas in high-disturbance scenarios (an average increase of 0.06 species) and decreased by an average of 0.16 species in low disturbance regime scenarios. Treated areas in the high-disturbance, local wood emphasis scenario experienced the greatest increase of an average of 2.05 species. Species diversity in that youngest cohort exhibited nearly identical patterns. The metric used to evaluate diversity, Simpson's D, showed declines in untreated areas in low disturbance regime scenarios, and smaller increases in the high disturbance scenarios relative to treated areas under nearly all scenarios. The only treated areas that exhibited a decline were in the low disturbance regime scenario that employed modeled recent trends silviculture.

Table A18. *Comparison of selected climate change adaptation and resiliency related metrics for northern hardwoods communities in western Massachusetts, focusing on species richness, and diversity, both as described earlier. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Species richness, 0-10 years

	Treated area Scenario								Untreated area Scenario							
Subtable 5	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	1.6	3.3	3.4	3.3	1.6	3.1	3.4	3.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Post-treatment	2.4	4.7	5.0	4.8	2.4	4.6	5.1	4.9	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Post-10 yr	2.6	5.1	5.3	5.1	2.4	5.0	5.4	5.3	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3
Post-30 yr	2.6	5.8	5.8	5.6	1.5	3.9	5.2	4.9	0.8	0.6	0.6	0.6	0.2	0.2	0.2	0.2
Post-55 yr	2.1	5.3	6.0	5.8	1.3	3.6	4.8	4.5	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.2
Post-75 yr	2.0	4.7	5.4	5.3	1.3	3.2	4.2	4.1	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.2

Species diversity (Simpson's D), 0-10 years

	Treated area Scenario								Untreated area Scenario							
Subtable 6	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	0.36	0.53	0.53	0.54	0.36	0.52	0.54	0.53	0.14	0.15	0.14	0.15	0.14	0.15	0.15	0.15
Post-treatment	0.42	0.57	0.57	0.56	0.43	0.57	0.58	0.56	0.18	0.20	0.19	0.20	0.19	0.19	0.19	0.19
Post-10 yr	0.41	0.66	0.67	0.66	0.40	0.65	0.67	0.67	0.12	0.13	0.13	0.12	0.12	0.12	0.13	0.12
Post-30 yr	0.44	0.66	0.66	0.63	0.37	0.59	0.65	0.63	0.23	0.20	0.20	0.20	0.08	0.08	0.08	0.08
Post-55 yr	0.44	0.66	0.68	0.67	0.35	0.56	0.63	0.61	0.20	0.20	0.20	0.20	0.10	0.10	0.09	0.09
Post-75 yr	0.41	0.62	0.64	0.63	0.36	0.54	0.59	0.58	0.17	0.17	0.18	0.18	0.09	0.09	0.10	0.09

As with spruce-fir forests, age class richness is an important, but not the only structural resilience metric. Once again, similar patterns were observed as the species richness and diversity metrics (Table A19). Untreated areas in low disturbance scenarios lost an average of 0.46-0.56 age classes. The effect of modeled recent trends silviculture was variable; treated areas in the high disturbance scenario exhibited the greatest gains of any scenario (an average increase of 0.75 age classes); in the low disturbance scenarios recent trends silviculture only afforded an average gain of only 0.04 age classes. Of note is that in the untreated areas, the same scenario (high disturbance, recent trends) offered the greatest increases. Treated areas using the modeled CSF/COF practices offered consistent gains over the modeled time period regardless of disturbance regime, of between 0.45-0.61 age classes on average. Untreated areas in the high disturbance scenarios that employed CSF/COF practices offered more modest gains of 0.45-0.51 age classes on average.

Table A19. *Comparison of selected climate change adaptation and resiliency related metrics for northern hardwoods communities in western Massachusetts, focusing on age class richness. Values represent the average number of age classes (using the initial communities cohorts) present. Summaries for acres treated in the first 5-year period after model initialization are on the left; and for areas untreated over the course of the model are on the right. Time prior to, and after treatment, is displayed in rows (though untreated areas were not subject to silviculture in the model, data from the same time steps are displayed). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

	Age class richness															
	Treated area Scenario								Untreated area Scenario							
Subtable 7	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Acres	12,120	23,329	34,502	27,533	12,732	22,949	36,525	27,873	164,394	142,647	72,448	108,732	97,047	142,583	72,180	108,498
Pre-treatment	4.93	6.24	6.39	6.29	4.97	6.25	6.37	6.27	3.17	3.25	3.26	3.27	3.20	3.25	3.27	3.27
Post-treatment	5.10	6.32	6.40	6.29	5.10	6.30	6.37	6.29	3.24	3.34	3.35	3.36	3.28	3.34	3.35	3.36
Post-10 yr	5.46	6.76	6.83	6.73	5.49	6.75	6.81	6.71	3.42	3.51	3.53	3.54	3.46	3.51	3.54	3.53
Post-30 yr	5.82	6.87	6.89	6.84	5.41	6.79	6.93	6.83	3.98	3.91	3.96	3.94	3.32	3.34	3.38	3.37
Post-55 yr	5.84	6.95	6.99	6.97	5.21	6.82	7.01	6.92	4.00	3.90	3.96	3.93	3.03	2.99	3.05	3.02
Post-75 yr	5.67	6.84	6.94	6.91	5.01	6.70	6.87	6.80	3.81	3.70	3.78	3.74	2.74	2.69	2.76	2.74

Case Study 5: Resiliency of Ecosystem Carbon Stocks

Looking at outcomes in different treatment domains on a per-acre basis remains important for carbon as it is for indicators of forest ecosystem health and resilience. Once again, signals of stability emerge when analyzing data that separate live tree dry biomass removed from hurricanes of strength EF2 or greater. Data separating removals by all disturbances for more discrete analyses were not available.

In scenarios with hurricanes, areas that were harvested early in the modeling period lost 58.5%-72.5% less carbon on a per-acre basis to hurricane damage than areas that were not harvested (Table A20). The most severe losses were from the first modeled hurricanes, in which the scenario employing recent trends silviculture and the scenario using CSF/COF silviculture with local wood emphasis reduced those early losses the greatest (60.1% and 41.0%, respectively). Salvage harvesting can be used to great benefit for ecological and carbon outcomes in some contexts, but its use has important tradeoffs. Focusing resources on salvaging timber and carbon after a disturbance as a primary strategy can require more expensive mobilization, diverting resources from tending of stands that require intervention at critical times (e.g. mast years, or releasing established regeneration without damage in a shelterwood sequence). Because salvage logging is far more expensive than standard logging and dangerous salvage logging conditions can endanger the lives of forest workers, gains from preventative management in an uncertain world become more important. Even after the first modeled hurricane, the amplitude of damage from subsequent hurricanes is far less (61.4%-137.8%), reinforcing that well-planned silviculture can offer persistent stability of ecosystem services.

Table A20. *Comparison of above ground live tree biomass density (tons per acre) killed by EF2 and greater hurricanes in areas treated by silviculture early in the model (left) and not treated by silviculture at any point in the model (right). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Above ground live tree dry biomass removed per acre by hurricanes with strength EF2 and greater, tons per acre

	Treated area Scenario								Untreated area Scenario							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
2020	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2025	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2030	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2035	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2040	25.33	31.24	26.71	26.86	—	—	—	—	40.56	36.49	37.66	36.81	—	—	—	—
2045	1.58	1.33	2.40	2.13	—	—	—	—	4.13	4.17	4.35	4.28	—	—	—	—
2050	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2055	14.22	10.29	10.68	9.85	—	—	—	—	22.95	23.39	23.86	23.43	—	—	—	—
2060	0.00	0.00	0.00	0.00	—	—	—	—	0.00	0.00	0.00	0.00	—	—	—	—
2065	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2070	0.01	0.04	0.04	0.02	—	—	—	—	0.09	0.08	0.10	0.11	—	—	—	—
2075	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2080	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2085	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2090	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2095	3.18	2.25	3.56	2.98	—	—	—	—	7.45	7.45	7.43	7.54	—	—	—	—
2100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Silvicultural treatments also moderated losses of live tree carbon from non-hurricane disturbances and hurricanes with strength less than EF2 (Table A21). Areas treated early in the model with the modeled recent trends silviculture still showed reduced mean losses from non-hurricane disturbances (6.9% less in the high-disturbance scenario, and 7.4% less in the low disturbance scenario), and a smaller range of losses, but less than areas treated with CSF/COF (19.4% less in the high-disturbance scenario, and 7.4% less than the low disturbance scenario). While long-run mean losses in treated areas were less, treated areas occasionally exhibited slightly greater losses at individual time over untreated areas. Areas treated with modeled CSF/COF silviculture showed a smaller range of losses from time step to time step (i.e., more stability) on the order of 43.0%-70.0% less range than untreated areas in the high disturbance scenarios, and 24.0%-39.7% less range than untreated areas in the low disturbance scenarios. The scenarios with the greatest reductions in mean losses and increases in stability were the local wood emphasis and combined emphasis scenarios. Within the high-disturbance scenarios with both hurricanes and the subset of background disturbances that were modeled, the modeled subset of disturbances removed 24.4%-30.1% more above ground live tree dry biomass than hurricanes of strength EF2 or greater.

Table A21. *Comparison of above ground live tree biomass density (tons per acre) killed by non-hurricane disturbances and EF1 hurricanes in areas treated by silviculture early in the model (left) and not treated by silviculture at any point in the model (right). Scenarios are numbered as follows: (1) High Disturbance Recent Trends, (2) High Disturbance Reserve Emphasis, (3) High Disturbance Local Wood Emphasis, (4) High Disturbance Combined Emphasis, (5) Low Disturbance Recent Trends, (6) Low Disturbance Reserve Emphasis, (7) Low Disturbance Local Wood Emphasis, and (8) Low Disturbance Combined Emphasis.*

Above ground live tree dry biomass removed per acre by non-hurricane disturbances and EF1 hurricanes, tons per acre																
	Treated area								Untreated area							
	Scenario								Scenario							
	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
2020	0.26	0.18	0.19	0.18	0.20	0.18	0.21	0.21	0.18	0.20	0.20	0.20	0.18	0.20	0.20	0.20
2025	1.55	1.55	1.63	1.56	1.33	1.30	1.35	1.36	1.52	1.61	1.46	1.54	1.25	1.39	1.27	1.33
2030	0.49	0.58	0.48	0.45	0.31	0.39	0.35	0.32	0.70	0.74	0.71	0.72	0.48	0.53	0.50	0.52
2035	0.96	1.10	1.02	1.03	0.64	0.69	0.67	0.62	1.47	1.53	1.44	1.48	0.90	0.99	0.93	0.97
2040	4.06	4.02	4.06	3.82	0.87	0.95	0.83	0.83	4.33	5.77	5.65	5.80	1.12	1.20	1.17	1.18
2045	5.69	5.98	5.53	5.44	0.45	0.50	0.45	0.45	7.24	7.54	7.53	7.52	0.52	0.58	0.56	0.57
2050	1.24	1.26	1.28	1.24	1.09	1.03	1.02	1.00	1.50	1.72	1.57	1.65	1.22	1.34	1.25	1.30
2055	9.25	8.83	6.49	6.66	1.20	1.07	0.93	0.90	9.62	10.37	9.78	10.25	1.39	1.51	1.45	1.48
2060	3.75	3.06	2.61	2.59	0.77	0.66	0.59	0.60	4.40	4.34	4.18	4.21	0.80	0.88	0.83	0.86
2065	5.26	4.22	4.10	3.90	3.16	3.01	2.72	2.64	4.77	5.64	5.00	5.41	3.36	3.71	3.45	3.59
2070	3.11	2.06	2.32	2.14	0.50	0.35	0.37	0.35	3.81	3.95	3.79	3.84	0.47	0.52	0.49	0.50
2075	4.10	3.32	2.94	2.76	2.86	2.35	2.29	2.26	3.97	4.39	3.87	4.17	2.90	3.27	3.01	3.15
2080	5.56	3.94	3.57	3.43	3.13	2.70	2.42	2.33	5.08	5.51	4.92	5.31	3.27	3.60	3.38	3.52
2085	10.84	8.27	7.50	7.28	1.20	1.07	1.02	0.99	12.82	12.58	12.62	12.55	1.31	1.46	1.37	1.44
2090	2.03	1.53	1.45	1.45	1.17	1.05	0.98	1.02	1.95	2.13	1.95	2.06	1.24	1.37	1.27	1.34
2095	10.59	8.79	7.37	7.46	0.90	0.81	0.71	0.69	10.78	10.85	10.49	10.61	0.91	1.03	0.93	0.99
2100	4.77	3.61	3.40	3.30	2.61	2.35	2.20	2.18	4.45	4.82	4.39	4.65	2.70	2.99	2.79	2.92