Land Sector Report

A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study

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Acknowledgements

This report was prepared by the Harvard Forest, a department of Harvard University, for the Commonwealth of Massachusetts as part of the Decarbonization Roadmap Study.

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1 Executive Summary

The following technical report describes an analysis of alternative land-use and land-cover (LULC) change scenarios and the associated consequences for stocks and fluxes of terrestrial carbon in the Commonwealth of Massachusetts. The work was conducted by a team of researchers at the Harvard Forest working as part of the Commonwealth's Decarbonization Roadmap Study.

In Massachusetts, forests cover 64% of the land area. Forests, therefore, are of principal concern when estimating terrestrial carbon budgets. Forest ecosystems sequester atmospheric carbon as biomass as they grow and they emit carbon back to the atmosphere when they are stressed or disturbed, whether by natural or human forces. The analyses presented here rely on a series of landscape simulations to estimate changes in terrestrial carbon, primarily forest carbon, during the period spanning 2020 to 2050 and focus on three primary drivers of change: forest ecosystem dynamics (such as forest growth), land-cover change, and commercial forestry.

The analyses utilize the LANDIS-II/PnET ecosystem model to simulate aboveground forest carbon dynamics, including species-specific tree establishment, growth, competition, and mortality. The effects of future climate change and increasing CO_2 concentrations are explicitly incorporated into this ecosystem model. Land-cover change is simulated with the Dinamica EGO cellular automata model, which is subsequently incorporated into the LANDIS-II/PnET model to estimate impacts of land-cover change on forest carbon. Commercial forestry is also simulated within the LANDIS-II/PnET model, and the fate of harvested carbon is tracked using a conventional carbon allocation approach. Non-forest carbon is estimated using a spatially explicit gain-loss bookkeeping model, which utilizes static carbon density estimates for Built, Pasture & Agricultural, and all other land cover classes. Similarly, soil organic carbon is tracked using static carbon density coefficients associated with all land-cover classes.

The goal of the analysis is to estimate the impact of five land-use scenarios on stocks and fluxes of terrestrial carbon throughout the Commonwealth to the year 2050. Impacts are estimated using simulation models in a counterfactual framework, which assesses the net effect of LULC change (e.g., forest loss, commercial forestry) by comparing the outcome from specified land-use scenarios to estimates of what would have happened in the absence of the LULC change. The estimated impacts include both the direct emissions associated with removing trees and disturbing soil, and the secondary impacts associated with altered carbon pathways onsite after the LULC change event. For example, when converting from a forest lot to a house lot, the impact includes the emissions associated with the carbon removed in the cleared trees and disturbed soil, plus all of the carbon that would have been sequestered by that forest to the year 2050. In the case of forestry, carbon is removed with the trees and much of that is emitted into the atmosphere; however, in contrast to development, carbon sequestration continues after harvesting and, in some conditions, the rate of sequestration can be enhanced as more resources are made available to unharvested and newly established trees.

The five land-use scenarios were developed in consultation with staff at the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) and the Massachusetts Department of Conservation and Recreation (DCR). They include two baseline land-use scenarios, which emulate patterns of LULC change observed in the past 30 years, through to the year 2050. In one baseline scenario (BL_A), the annual area harvested is consistent throughout the simulation with this rate based on the recent average area harvested. The other baseline scenario (BL_{MV}) maintains a consistent volume/mass of harvested wood each year based on recent trends (2001 to 2017). Both baseline scenarios emulate the spatial patterns of observed land-cover change since 1990 and have a rate of change associated with projections of population growth. Two other scenarios envisioned changes to policy that affect commercial forestry, which include improved silvicultural practices as well as new markets for wood products leading to more area harvested. Like the baseline scenarios the "Policy Runs" have two variants, one with consistent area (PR_A) harvested and one with consistent volume/mass (PR_{MV}) harvested. Both Policy Runs include the same types, rates, and spatial patterns of land-cover change as in the baseline scenarios. The final scenario is the High Population Growth with constant harvest area (HP_A) run, which assumes 35% more development but has identical patterns of commercial forestry as the BL_A run.

The results show only small differences among the simulated scenarios in terms of their impact on statewide carbon stores in 2050 (Figure 1). The primary mechanism controlling terrestrial forest carbon dynamics is the continued growth of forests across the Commonwealth, which are still maturing and actively growing in tree size and forest biomass, following regional farm abandonment and reforestation in the nineteenth and early twentieth centuries and subsequent impacts of the 1938 hurricane and logging in the last century. Simulated climate change and the associated increase in atmospheric CO_2 concentrations increases the rate of forest growth and carbon sequestration. Additionally, forest conversion and forest harvesting both reduce carbon storage from its maximum potential, varying only slightly among the specific scenarios.

In all scenarios, forest growth exceeds the removals by both harvesting and forest conversion, such that Massachusetts' forests continue to be a net carbon sink, with between 36 to 39% more live carbon stored in forests by 2050. In a counterfactual simulation with no harvesting or forest loss for development, carbon stores increase 49% by 2050. Forest harvesting and forest conversion reduce the potential carbon stores in 2050 by between 9.9 and 11.6 Tg C, indicating that a reduction in these land uses could increase stocks of live forest carbon by up to 13%.

Forest loss to development in the scenarios was concentrated around urban areas and along the I-95 and I-495 corridors in accordance with statewide housing growth forecasts. Forest loss affected 45,104 and 57,776 ha within the baseline and High Population scenarios, respectively, and reduced carbon stores by 5.3 to 6.4 Tg (19.5 to 23.5 MMT of CO_2eq) relative to a scenario with no LULC change. Of that, approximately 60% was associated with the direct emissions caused by the clearing of trees (i.e., above and belowground live tree biomass), and 40% was due to the forgone carbon sequestration calculated out to the year 2050. An analysis of the scenarios' land-cover change impacts on soil organic carbon suggests that an additional 10.9 to 13.9 Tg C (40.0 to 51.0 MMT of CO_2eq) could be emitted due to development.[1]

Commercial forestry was projected to occur on 216,453 to 341,249 ha over the 30-year simulations and was concentrated in the western half of the Commonwealth. Harvesting directly removes between 14.4 and 22.6 Tg of live carbon (C), depending on the scenario. Using simple yet flexible carbon accounting methods, we estimate that of the total removed carbon, approximately 34% of the carbon remains in storage as wood product, landfilled material, or slash on the landscape in 2050. Unlike forest loss through land use conversion

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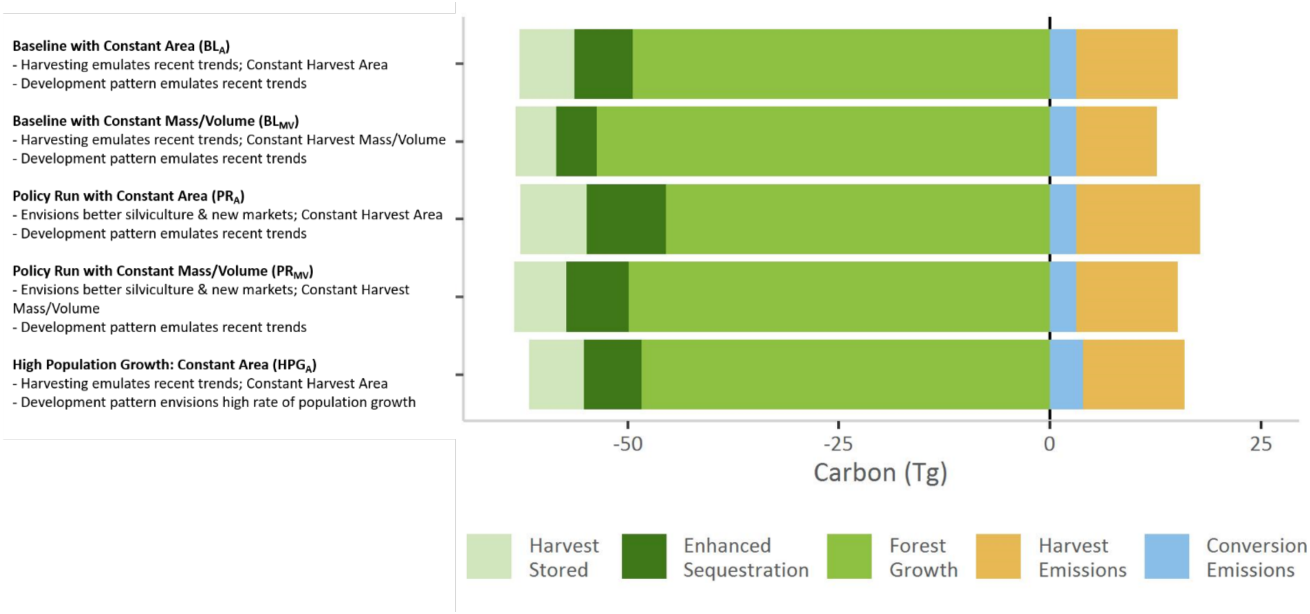
[1] This estimate is based on soil organic carbon coefficients from the Massachusetts Resilient Forests, which are higher than most previously published estimates. See section 3.7 for details. See also: Regenerative Design Group, "News - Massachusetts Healthy soils action plan: Updates." https://www.regenerativedesigngroup.com/healthy-soils-action-plan/; and, West, L, S Wills, and T Loecke. "Rapid Carbon Assessment (RaCA) Methodology," 2013, 9.

(for example, converting a hectare of forest to a hectare of hard-scape development), which prevents future carbon sequestration, selective harvesting often results in increased rates of sequestration in the remaining un-harvested forest. Therefore, the net impact of commercial forestry in 2050, after accounting for the fate of the harvested wood and the effect on forest growth rates, ranges from 4.7 to 5.4 Tg C, depending on the scenario.

Importantly, these analyses do not consider the potential effects of major natural disturbances, such as hurricanes or insect infestations. Such events are almost certain to occur before 2050 and, when they do, they will negatively impact Massachusetts' forest carbon stock, likely causing major carbon emissions from damaged forests and reducing total carbon stocks. Similarly, the scenarios in this study do not explicitly include any major technological changes that may alter the rate or pattern of LULC change in the Commonwealth, such as a large-scale build out of ground based solar or new energy transmission corridors. These are important areas for future research.

Figure 1: Simulated changes in terrestrial carbon stocks between 2020 and 2050 as affected by five alternative land-use scenario overview and impact on live carbon and emissions by year 2050.



2 Introduction

Increasing concentrations of CO_2 in the atmosphere is the primary driver of global climate change.[2] Terrestrial carbon, cycled through soil and vegetation, plays a key role in regulating the climate system. Forest ecosystems, in particular, serve as a critical carbon sink—as forests grow, they sequester atmospheric CO_2 and store it as terrestrial carbon—collectively storing an equivalent of as much as 30% of global fossil fuel emissions each year.[3] The strength of the forest carbon sink is variable and strongly influenced by the rate, pattern, and intensity of land-use and land-cover (LULC) change.[4] [5] Strategies to mitigate climate change must consider the impacts of LULC change on terrestrial carbon. This report describes projections of terrestrial carbon in Massachusetts, as it is affected by alternative scenarios of LULC change. The analyses focus on three principal drivers of change:

1. ecosystem processes, especially forest growth;
2. land-cover change, primarily forest conversion to developed uses; and,
3. commercial forestry, including the fate of harvested wood.

Today, about 64% of Massachusetts is covered by forests.[6] Estimates vary, but the trees in Massachusetts' forests store between 100 and 120 million metric tons (MMT or Tg) of carbon.[7] [8] [9] [10] For perspective, if the Commonwealth's forests were to suddenly burn up or decompose, they would return 376 to 451 MMT of CO_2eq to the atmosphere, and the impact on climate change would be the equivalent of over five years of fossil fuel emissions in Massachusetts (at 2017 rates).[11] Forest soils also store a massive amount of carbon; new estimates suggest the Commonwealth's soil carbon pool may be as high 373.7 Tg;[12]. Given its size, protecting Massachusetts' forests, along with their stores of terrestrial carbon and their capacity to continue

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[2] IPCC, "Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers," 2013.

[3] Pan et al., "A Large and Persistent Carbon Sink in the World's Forests," *Science* 333, no. 6045 (2011): 988–93.

[4] Thompson et al., "The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts, USA," *Ecological Applications* 21, no. 7 (2011): 2425–44.

[5] Foley et al., "Global Consequences of Land Use," *Science* 309, no. 5734 (2005): 570–74.

[6] Pasquarella and Holden, "Annual Land Cover Products for Massachusetts," 2019. DOI: 10.5281/ZENODO.3531893

[7] USDA Forest Service, Forest Inventory and Analysis Program, Wed Oct 28 15:51:30 GMT 2020. Forest Inventory EVALIDator web-application Version 1.8.0.01. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station.

[8] Thompson et al., "The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts, USA."

[9] Domke et al., "Greenhouse Gas Emissions and Removals from Forest Land , Woodlands , and Urban Trees in the United States , 1990-2018 Appendix 1 .– National Scale Estimates for Individual States , 1990-2018," *USDA US Forest Service*, 2020, 1–5.

[10] Reinmann et al., "Assessing the Global Warming Potential of Human Settlement Expansion in a Mesic Temperate Landscape from 2005 to 2050," *Science of the Total Environment* 545–546 (2016): 512–24.

[11] Commonwealth of Massachusetts. "GHG Emmissions and Mitigation Policies." https://www.mass.gov/info-details/ghg-emissions-and-mitigation-policies#:~:text=Table%20of%20Contents-,Introduction,Warming%20Solutions%20Act%20(GWSA .

[12] Regenerative Design Group, "News - Massachusetts Healthy soils action plan: Updates." https://www.regenerativedesigngroup.com/healthy-soils-action-plan/

to sequester large amounts of carbon into the future, is among the most important considerations for the Commonwealth with respect to its efforts to achieve Net Zero emissions by 2050.

In addition to storage, Massachusetts' forests also sequester carbon. Sequestration describes the rate of carbon uptake; or the amount of carbon that is drawn from the atmosphere into trees via photosynthesis over a specified increment of time, typically one year. Like many temperate forests throughout the world,[13] trees within Massachusetts forests are regrowing following an era of agricultural land use, and thus sequestering carbon relatively quickly. An average hectare (about two football fields) of mature forest in Massachusetts sequesters between one and one and a half tons of carbon each year.[14] [15] The current rate of growth for these forests is a function of local growing conditions, species present, the climate and soil, and the specific history of land use.[16] When Europeans colonized New England, the Commonwealth's forest stored between 250 to 500 Tg of aboveground carbon within the region's forests,[17] although it is impossible to know for sure. As settlers cleared, burned, and logged the landscape, their activities forced a large percentage of the forest carbon back into the atmosphere as CO_2. From circa 1600 to 1850, more than 50% of the forested area was cleared, and what was not cleared was heavily cut over (Figure 2). Then, in the mid-nineteenth century, vast areas of pasture and cropland were abandoned from active agricultural use for a host of economic reasons, and the forest began a long period of natural recovery. Forests dominated by native tree species reclaimed fields and accrued carbon as they grew. Given the longevity of the trees and an ongoing history of forest harvesting and disturbances, forests across Massachusetts are still recovering. Most dominant trees in the Commonwealth's forests are young, between 100 and 150 years, and are accelerating their growth.[18] The net accumulation of carbon in Massachusetts' forests due to sequestration, also called the net biome production,[19]

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[13] Cook-Patton et al., "Mapping Carbon Accumulation Potential from Global Natural Forest Regrowth," *Nature* 585, no. 7826 (2020): 545–50.

[14] Finzi et al., "The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change," *Ecological Monographs*, 2020.

[15] USDA Forest Service, Forest Inventory and Analysis Program, Wed Oct 28 15:51:30 GMT 2020. Forest Inventory EVALIDator web-application Version 1.8.0.01. St. Paul, MN: U.S. Department of Agriculture, Forest Service, Northern Research Station. [Available only on internet: http://apps.fs.usda.gov/Evalidator/evalidator.jsp]

[16] Thompson et al., "Four Centuries of Change in Northeastern United States Forests," ed. Bond-Lamberty, *PLoS ONE* 8, no. 9 (2013): e72540.

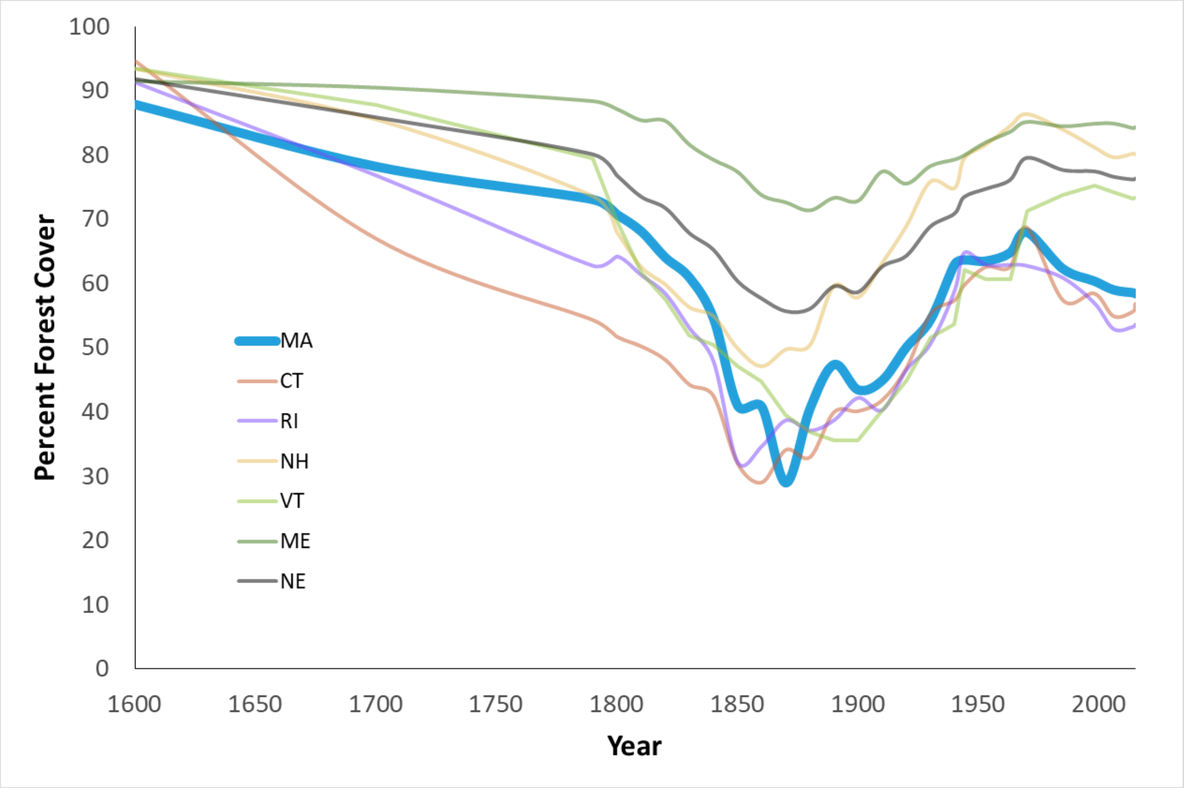
[17] This rough estimate was obtained by multiplying the 90% land area in the state that was assumed to be forested by a low (125Mg/ha) and high (250/Mg/ha) estimate of old growth forest carbon in eastern forest (see sub-references a-d) then subtracting 25% to account for disturbance impacts. (a) McGarvey et al., "Carbon Storage in Old-Growth Forests of the Mid-Atlantic: Toward Better Understanding the Eastern Forest Carbon Sink," *Ecology* 96, no. 2 (2015): 348–54. (b) Keeton et al.. "Late-Successional Biomass Development in Northern Hardwood-Conifer Forests of the Northeastern United States." *Forest Science* 57, no. 6 (2011): 489–505. (c) Gunn et al Late-successional and old-growth forest carbon temporal dynamics in the Northern Forest (Northeastern USA) *Forest Ecology and Management* (2013). (d) Whitney, G. "From Coastal Wilderness to Fruited Plain: A History of Environmental Change in Temperate North America from 1500 to the Present". Cambridge University Press, 1994.

[18] Finzi et al., "The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change."

[19] Chapin et al., "Reconciling Carbon-Cycle Concepts, Terminology, and Methods," *Ecosystems* 9, no. 7 (2006): 1041–50.

has been estimated between 1.5 and 2.5 Tg yr^{-1} (5.5 and 9.2 MMT of CO_2eq, respectively), depending on the methodology and assumptions.[20] [21] [22] [23] [24]

Figure 2: Change in Forest Cover Since 1600 throughout New England.[25]



That estimate of net biome production represents the amount of carbon sequestered in one year minus the amount emitted from the forests through natural and human processes. The fact that net biome production is positive means that, for now, the amount of carbon sequestered due to forest growth exceeds that emitted due to land-use and land-cover change. Indeed, estimates of growth exceed estimates of removals by a factor

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[20] Thompson et al., “The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts, USA.”

[21] Duveneck and Thompson, “Social and Biophysical Determinants of Future Forest Conditions in New England: Effects of a Modern Land-Use Regime,” *Global Environmental Change* 55, no. November 2018 (2019): 115–29.

[22] Reinmann and Hutyra, “Edge Effects Enhance Carbon Uptake and Its Vulnerability to Climate Change in Temperate Broadleaf Forests,” *Proceedings of the National Academy of Sciences of the United States of America* 114, no. 1 (2017): 107–12.

[23] Harris et al., “Attribution of Net Carbon Change by Disturbance Type across Forest Lands of the Conterminous United States,” *Carbon Balance and Management* 11, no. 1 (2016).

[24] Domke et al., “Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, and Urban Trees in the United States , 1990-2018 Appendix 1 . National Scale Estimates for Individual States , 1990-2018,” 2020, 1990–2018.

[25] Figure adapted from Foster, D., et al. 2017. *Wildlands and woodlands, farmlands and communities: broadening the vision for New England*. Harvard Forest, Petersham, Massachusetts, USA.

of three to five across the northeast, depending on the source.[26] [27] Natural processes that emit carbon include ecosystem respiration, tree death due to competition or senescence, and disturbances such as windfall and insects. After trees die, decomposition slowly releases forest carbon back into the atmosphere. The major human processes that cause forest carbon emissions to the atmosphere are forest loss and forest harvesting, which we combine as LULC change.

In Massachusetts, commercial forestry and forest loss for developed uses are the two most significant human land-use activities affecting terrestrial carbon stores. These processes differ in extremely important ways in the manner that they impact subsequent carbon dynamics along with a whole host of other forest qualities and values. Forest loss is the permanent conversion of forest to non-forest cover-types such as residential or commercial landscapes. During the past 30 years, forest conversion in Massachusetts has occurred at an average rate of 1,800 ha yr^{-1} and has been primarily associated with expanding residential and commercial development, [28] [29] including associated road construction, powerline construction, and a range of infrastructure development. Forest conversion clears trees and disturbs the soil, which results in the emission of carbon stored locally. In addition, by permanently removing some or all of the trees, forest conversion greatly limits or even eliminates the capacity of the site for future carbon sequestration. Therefore, the impact of forest conversion on terrestrial carbon loss is equal to the sum of the direct emissions from clearing plus the forgone sequestration by the previous forest to a specified date.

The second important land-use activity that affects terrestrial carbon is commercial timber harvesting. Like forest conversion, harvesting removes a portion of the stored carbon. A typical commercial harvest in the Commonwealth removes 30 to 80% of live carbon. But unlike forest conversion, harvesting keeps soils largely intact, retains many trees, and allows the forest to regrow and therefore continue to sequester carbon. In addition, some of the removed carbon is not immediately returned to the atmosphere, but instead is stored in wood products. The percent stored in wood product is highly dependent on the wood and wood product industry and so, like harvesting practices, is subject to significant human control. For example, chips produced for burning will have a very short storage life, whereas timbers that become furniture or beams in buildings may last many decades. While the impacts of commercial forestry are often less intense and more ephemeral than forest conversion, it does occur over a much greater area; on average, 7,400 ha of Massachusetts' forests have a commercial timber harvest each year.[30]

This report describes the implications of potential future LULC change on terrestrial carbon dynamics, or net biome production. These analyses use a series of spatially explicit models to simulate forest growth and other ecosystem processes as they are affected by alternative scenarios of forest loss and commercial forestry. The models assume and incorporate the effects of future climate change, including increases in atmospheric CO_2 concentrations, warmer temperatures, and longer growing seasons; which are favorable to tree growth.[31]

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[26] Williams et al., "Disturbance and the Carbon Balance of US Forests: A Quantitative Review of Impacts from Harvests, Fires, Insects, and Droughts," *Global and Planetary Change* 143 (2016): 66–80.

[27] Butler, "Forests of Massachusetts, 2017," *USDA Resource Update FS-161*, no. August (2017): 2018–19.

[28] Olofsson et al., "Time Series Analysis of Satellite Data Reveals Continuous Deforestation of New England since the 1980s," *Environmental Research Letters* 11, no. 6 (2016): 1–8.

[29] Pasquarella and Holden, "Annual Land Cover Products for Massachusetts." DOI: 10.5281/ZENODO.3531893

[30] As calculated from Massachusetts Forest Cutting Plan data described in section 4.4 Timber Harvesting

[31] Duveneck and Thompson, "Climate Change Imposes Phenological Trade-Offs on Forest Net Primary Productivity," *Journal of Geophysical Research: Biogeosciences* 122, no. 9 (2017): 2298–2313.

Much of the analyses are focused on developing a baseline estimate of land-use carbon emissions. The baseline scenario can serve as a reference against which other land-use scenarios can be measured. The use of a baseline enables the assessment of the additionality of future policy or land-use decisions, an idea which is central to most current forest and land-use carbon policies and accounting schemes.[32] [33] The impact of any potential policy is determined in comparison to what would have occurred in the absence of that policy. In this analysis, the baseline is determined by the average rate, spatial pattern, and intensity of land use observed during the past thirty years. The impacts of the baseline are estimated by comparing the carbon stocks in 2050 to a counterfactual simulation with no LULC change. In addition to the baseline, the report describes the impacts of two other policy scenarios relative to the recent trends in land use. The specific scope of the analysis, including the attributes of the land-use scenarios that were examined, were determined by the Massachusetts Executive Office of Energy and Environmental Affairs (EEA) and Massachusetts Department of Conservation and Recreation (DCR).

While the analyses summarized in this report represent a detailed and mechanistic perspective on the potential future dynamics of terrestrial carbon within the Commonwealth, there is still much they do not consider. For one, the analyses do not explicitly incorporate land ownership or landowner behavior. This is an important limitation given that more than 65% of Massachusetts' forests are owned by individuals and families.[34] There are more than 30,000 privately-owned parcels greater than four hectares.[35] In the absence of regulatory or legal decisions about whether to develop or harvest timber from a parcel of land in Massachusetts, decisions are typically made by private owners, not by policymakers. Predicting and affecting behavior in such a dispersed decision-making context is extremely difficult and has been referred to as "The Tyranny of Small Decisions."[36] Therefore, the models used in this report do not attempt to predict behavior of actual landowners, nor do they recognize the boundaries between parcels, or even the distinctions between public and private land. Instead, the analyses emulate statistical trends regarding the frequency, intensity, and spatial distribution of the land-use regime. One important exception relates to land that is protected for conservation (e.g., through an easement or public ownership); protected land is not subjected to forest conversion. In the model, harvesting is allowed on most protected lands, which is consistent with actual practices.

Another important limitation relates to the risk of major natural disturbances. While the simulations do include small-scale wind disturbance, they do not include large-scale wind disturbances, such as hurricanes or tornadoes, and do not include insect infestations or disease outbreaks. It is highly probable that at least one major natural disturbance will impact the Commonwealth's forest carbon balance some time during the next 30 years.[37] [38] Consider, for example, that the 1938 Hurricane leveled as much as one-third of the trees within a

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[32] Mason and Plantinga, "The Additionality Problem with Offsets: Optimal Contracts for Carbon Sequestration in Forests," *Journal of Environmental Economics and Management* 66, no. 1 (2013): 1–14.

[33] Gren and Zeleke, "Policy Design for Forest Carbon Sequestration: A Review of the Literature," *Forest Policy and Economics* 70 (2016): 128–36.

[34] Butler et al., "The Forests of Southern New England, 2012 A Report on the Forest Resources of Connecticut, Massachusetts, and Rhode Island," *U.S. Department of Agriculture, Forest Service, Northern Research Station*, 2015, 1–42.

[35] Butler et al., "USDA Forest Service National Woodland Owner Survey," *Resource Bulletin NRS-99*, 2016.

[36] Odum, "Tyranny of Small Decisions," *BioScience* 32, no. 9 (1982): 728–29.

[37] MEMA and EOEA, "Massachusetts State Hazard Mitigation and Climate Adaptation Plan," 2018.

[38] Williams et al., "Disturbance and the Carbon Balance of US Forests: A Quantitative Review of Impacts from Harvests, Fires, Insects, and Droughts," *Global and Planetary Change* 143 (2016): 66–80.

150 km swath across central Massachusetts, prompting in the largest federal salvage logging operation in U.S. history.[39] Consider also that hurricanes in the north Atlantic are anticipated to increase in frequency and intensity with climate change[40] and that as Massachusetts forests increase in age and stature, they are more vulnerable to hurricane damage.[41] However, it is impossible to know when major disturbance events may occur or what their impacts will be when they do. Thus, while the report does not incorporate the risk of major natural disturbance, determining risk of loss and the permanence of storage are often built into forest carbon policies and accounting schemes.[42] [43] This is an important area for future consideration.

Finally, the report does not incorporate new or novel drivers of land-use change resulting from changing technologies or economies. Significantly, this report does not include any explicit analysis of new energy development, such as ground-based solar or electric transmission lines. Without recent observations to build a model from, any consideration of novel land-use drivers would need to incorporate distinct siting requirements, such as topography and proximity to required infrastructure, as well as social factors like land values and zoning requirements. The high population scenario provides insight into a potential higher rate of LULC change with more than 14,000 additional hectares of development built than the baseline population scenario, but the impacts and patterns are based on residential and commercial building development characteristics and not new energy development.

This report focuses exclusively on the impacts of LULC change on terrestrial carbon in Massachusetts during the period spanning 2020 to 2050. This information is critical for decision making in the context of mitigating climate change, yet it is also a partial view of a much more complex system. Forests and land offer much more than carbon storage. Forests filter and store drinking water and clean the air; they provide wildlife habitat, recreational opportunities, and countless other societal benefits;[44] these services are not considered here. It is also worth noting that forest LULC change in Massachusetts is coupled to regional- to global-scale markets. As such, land-use decisions made in Massachusetts have impacts on terrestrial carbon stored outside the Commonwealth's boundary (i.e., leakage). Finally, the temporal scope of these analyses constrains the perspective on land-use impacts. The 30-year scope represents only a small portion of a forests' life span, and the full impacts land-use decisions made today will not be fully realized in 2050. A more complete accounting of land-use impacts on human and natural systems is needed to understand the long-term systemic effects.

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[39] Long, *Thirty-Eight: The Hurricane That Transformed New England* (New Haven: Yale University Press, 2016).

[40] R.K. Pachauri, "Climate Change 2014 Synthesis Report Summary Chapter for Policymakers," *Ipcc*, 2014, 151.

[41] Boose, Chamberlin, and Foster, "Landscape and Regional Impacts of Hurricanes in New England," *Ecological Monographs* 71, no. 1 (2001): 27–48.

[42] Mason and Plantinga, "The Additionality Problem with Offsets: Optimal Contracts for Carbon Sequestration in Forests."

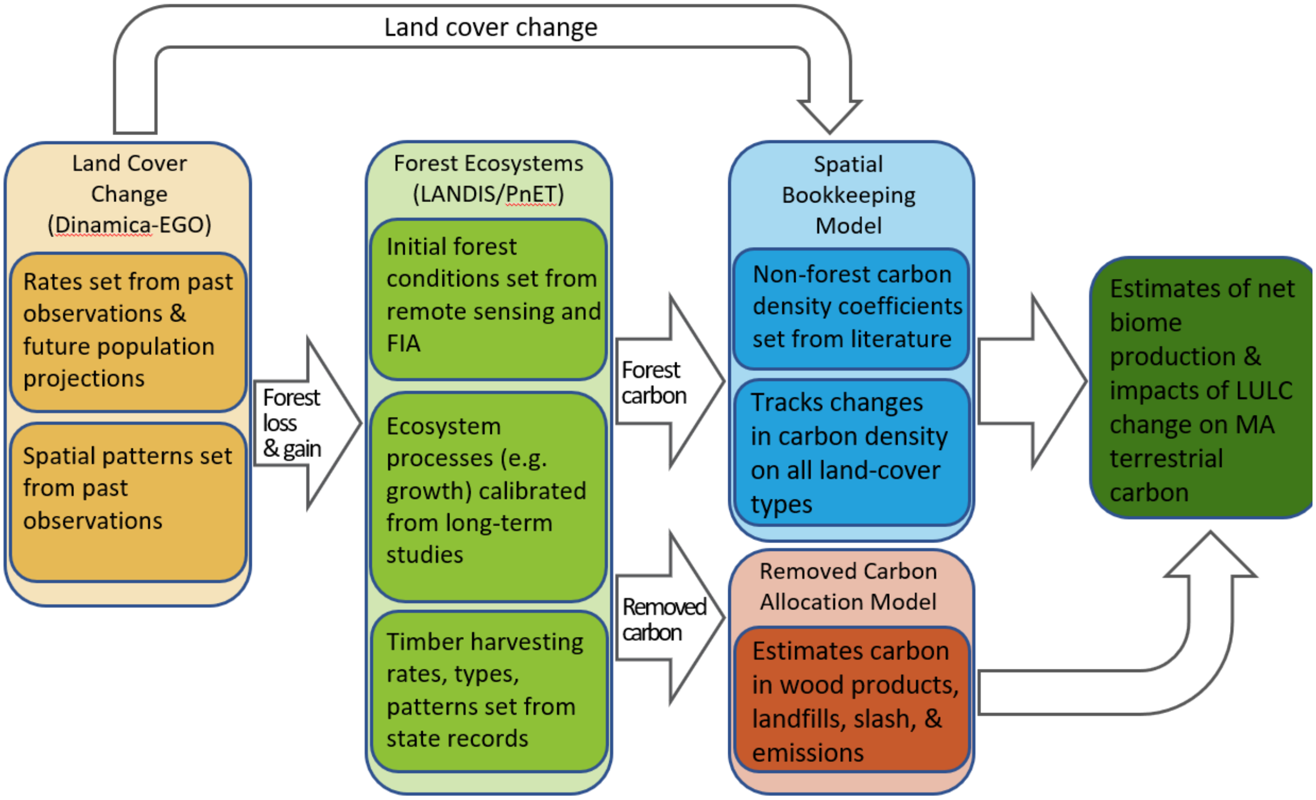
[43] Gren and Zeleke, "Policy Design for Forest Carbon Sequestration: A Review of the Literature."

[44] Blumstein and Thompson, "Land-Use Impacts on the Quantity and Configuration of Ecosystem Service Provisioning in Massachusetts, USA," ed. Nally, *Journal of Applied Ecology* 52, no. 4 (2015): 1009–19.

3 Methods

This study estimated LULC change impacts on future terrestrial carbon in Massachusetts by focusing on three primary drivers of change: (*i*.) forest ecosystem processes, (*ii*.) land-cover change, and (*iii*.) commercial timber harvesting. Within the forested areas of the Commonwealth, a mechanistic ecosystem model was used to simulate forest carbon dynamics as they were affected by natural and anthropogenic drivers, including forest growth, climate change, and LULC change (Figure 3). A cellular land-cover change model was used to simulate the conversion of forest cover to development and other land-cover transitions. A forest management sub-model was coupled to the ecosystem model to simulate the impacts of commercial timber harvesting. Harvested wood was tracked using a carbon allocation framework that estimated the proportion of removed wood as stored and emitted carbon through time. Each non-forest land-cover type was assigned a static carbon density, which was mapped and combined with the outputs from the ecosystem model, into a state-wide, spatially explicit carbon bookkeeping model, which tracked carbon dynamics using a gain-loss approach across all land-cover types and estimated regional terrestrial carbon stocks and fluxes from 2020 to 2050.

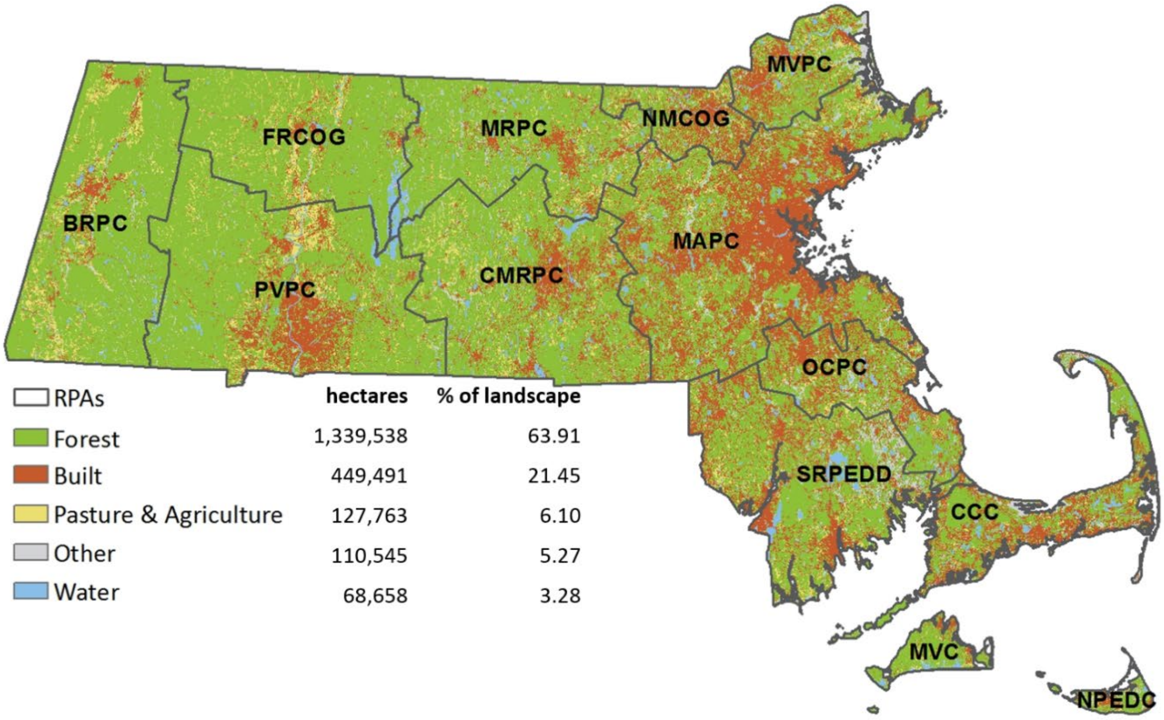
Figure 3. Simulation methodology flow chart



3.1 Study Area

The study area was the 20,960 km^2 land area of Massachusetts, including the mainland, islands, and inland water bodies (Figure 4). Forest is the dominant land cover type (64%) in the Commonwealth, and is dominated by early- to mid-successional tree species such as red maple (*Acer rubrum*), white pine (*Pinus strobus*), and red oak (*Quercus rubra*), with lesser amounts of late-successional, longer-lived species, such as beech (*Fagus grandfolia*) and hemlock (*Tsuga canadensis*). [45] [46] Built land is the next largest land cover (21%) and, while it is dispersed throughout the Commonwealth, is most prevalent and dense around the Boston, Worcester, and Springfield metro regions. For the purposes of this study, the Commonwealth was divided into 13 sub-regions based on Regional Planning Agency (RPA) boundaries and results were summarized at the Commonwealth and RPA scales. The spatial grain of analysis was 30-meters and simulations were performed using five-year time-steps, spanning the years 2020 to 2050.

Figure 4. Study area RPA sub-regions and land cover[47] in 2020.



3.2 Analytical Approach

The central goal of this analysis was to estimate the impact of five land-use scenarios (see section 3.8 below) on terrestrial carbon in Massachusetts by the year 2050. Calculating land-use impacts on terrestrial carbon requires explicit consideration of the ecosystem dynamics occurring in the background. For example, when a patch of Forest cover is converted to Built cover, the impact on carbon includes: (*1*) the direct emissions associated with removing the trees and disturbing the soil and (*2*) the forgone carbon sequestration that would have occurred in that Forest cover out to the year 2050 (Figure 5). Impacts are estimated using simulation models in a counterfactual framework, which assesses the net effect of a land use (e.g., forest loss or commercial forestry) by comparing outcome from simulated land-use scenarios to simulations of what

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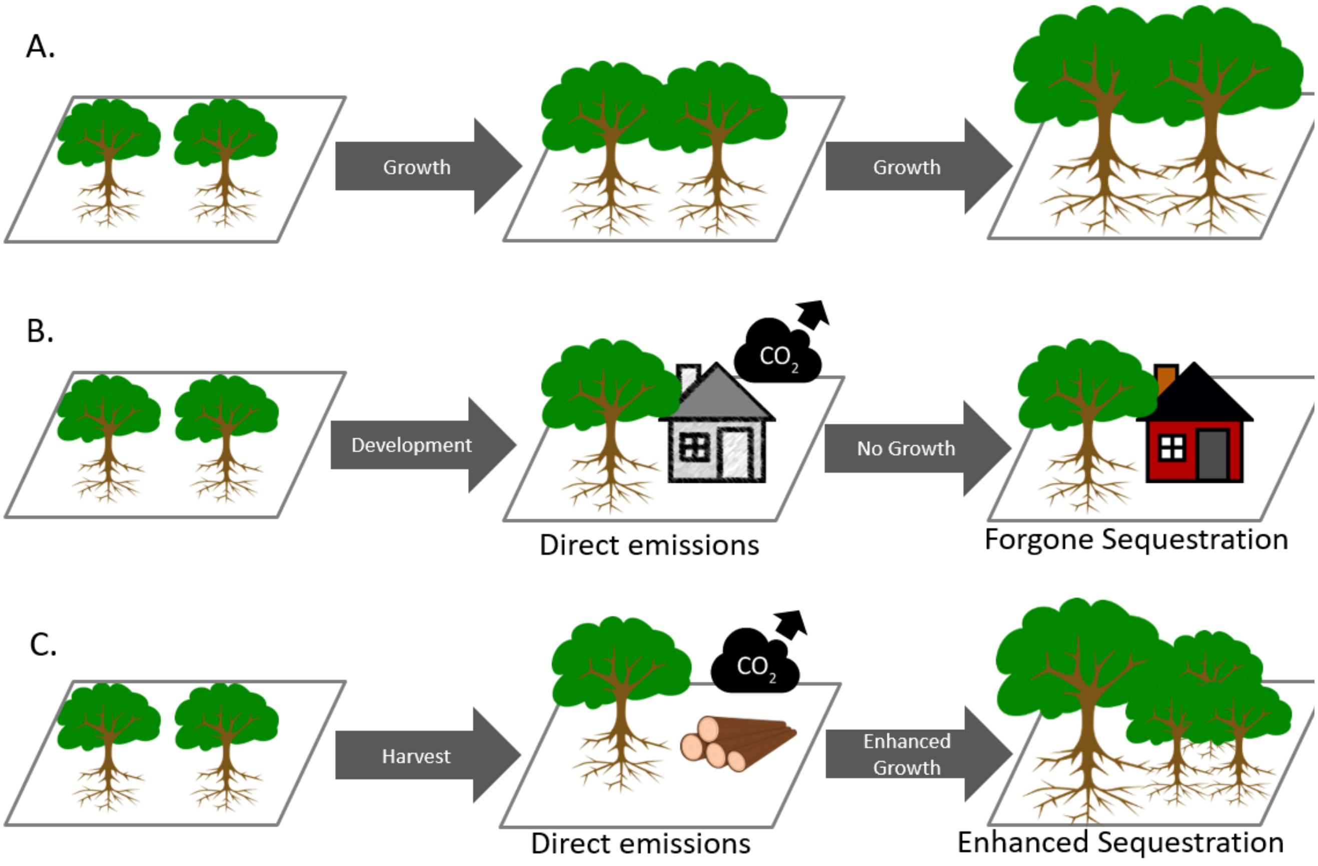
[45] Pasquarella and Holden.

[46] Thompson et al., “Four Centuries of Change in Northeastern United States Forests.”

[47] Pasquarella and Holden, “Annual Land Cover Products for Massachusetts.” DOI: 10.5281/ZENODO.3531893

would have happened in the absence of the land use.[48] First, a simulation with no land use was used to estimate the hypothetical carbon potential at 5-year time steps to 2050. Then, by incrementally introducing land uses into the simulations, the individual and aggregate impacts of each land-use were estimated. Thus, the impact of land use (i.e., land-cover change and commercial forestry) on terrestrial carbon was calculated as the difference in carbon between a simulation that included that land-use and a simulation where it was excluded.[49] A similar approach was used to estimate the effect of climate change on terrestrial carbon stocks—i.e., a simulation that held current climate conditions stationary was compared to a simulation that included the anticipated changes to climate to determine the difference in the carbon at 2050 and provide an estimated impact of climate change.

Figure 5. A conceptual diagram demonstrating the direct impacts (i.e., removals) and secondary impacts of land use disturbance via altered ecosystem dynamics. A) a site undergoes no land-use change resulting in undisturbed growth over time. B) a site undergoes development resulting in an initial direct emission of carbon (i.e. 70% of forest carbon is removed) followed by forgone sequestration due to the removal of vegetation and the uncertainties regarding altered growth and mortality of remaining trees in developed environments (implications of this assumption are outlined in the Discussion) C) a site undergoes a timber harvest resulting in an initial direct emission of carbon followed by enhanced sequestration as resources (light, water, nutrients) are made more available.



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[48] Ferraro, "Counterfactual Thinking and Impact Evaluation in Environmental Policy," in *Environmental Program and Policy Evaluation: Addressing Methodological Challenges. New Directions for Evaluation*, ed. Birnbaum and Mickwitz, 2009, 75–84.

[49] Sensu, Erb et al., "Unexpectedly Large Impact of Forest Management and Grazing on Global Vegetation Biomass," *Nature* 553 (2018): 73–76.

3.3 Forest Ecosystem Processes

The LANDIS-II [50] forest modeling framework was used to simulate forest ecosystem processes. LANDIS-II is a spatially interactive modeling framework that uses a series of modules to simulate and map changes in tree species-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.[51] [52] [53] [54] [55] [56]

LANDIS-II simulations were conducted on the 64% of the Commonwealth that is forested as delineated by the 2017 Continuous Change Detection and Classification (CCDC) land-cover map,[57] plus an additional 0.33% of the Commonwealth (6,603 ha) that was classified as Pasture & Agriculture or Other, but was reforested during the land cover simulations (see section 3.4 below). The computational demands of simulating ecosystem processes on more than 21 million cells were substantial and it was necessary to divide the Commonwealth into a northern and southern half, run each separately, then reassemble the resulting maps and tabular outputs.

The PnET succession module for LANDIS-II,[58] which is principally derived from the PnET-II ecophysiology model,[59] was used to simulate tree establishment, tree species competition and succession, and growth rates. The model produces species-specific maps of aboveground carbon at each timestep and tracks species cohort biomass with the Output Biomass Community Extension.[60] The combination of 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.[61] Edaphic conditions (e.g., soil water-holding capacity) were estimated

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[50] Scheller et al., “Design, Development, and Application of LANDIS-II, a Spatial Landscape Simulation Model with Flexible Temporal and Spatial Resolution,” *Ecological Modelling* 201, no. 3–4 (2007): 409–19.

[51] Scheller and Mladenoff, “A Spatially Interactive Simulation of Climate Change, Harvesting, Wind, and Tree Species Migration and Projected Changes to Forest Composition and Biomass in Northern Wisconsin, USA,” *Global Change Biology* 11, no. 2 (2005): 307–21.

[52] Xu, Gertner, and Scheller, “Uncertainties in the Response of a Forest Landscape to Global Climatic Change,” *Global Change Biology* 15, no. 1 (2009): 116–31.

[53] Thompson et al., “The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts”

[54] Jonathan Thompson, Kathy Fallon Lambert, David Foster, Meghan Blumstein, Eben Broadbent, “Four Scenarios for the Future of the Massachusetts Landscape” (Petersham, MA: Harvard Forest, Harvard University, 2014).

[55] Duveneck et al., “Recovery Dynamics and Climate Change Effects to Future New England Forests,” *Landscape Ecology* 32, no. 7 (2017).

[56] Duveneck and Thompson, “Social and Biophysical Determinants of Future Forest Conditions in New England: Effects of a Modern Land-Use Regime,” *Global Environmental Change* 55, no. January (2019): 115–29.

[57] Pasquarella and Holden, “Losing Ground 6, Annual Land Cover Products for Massachusetts.,” 2019. DOI: 10.5281/ZENODO.3531893

[58] de Bruijn et al., “Toward More Robust Projections of Forest Landscape Dynamics under Novel Environmental Conditions: Embedding PnET within LANDIS-II,” *Ecological Modelling* 287 (2014): 44–57.

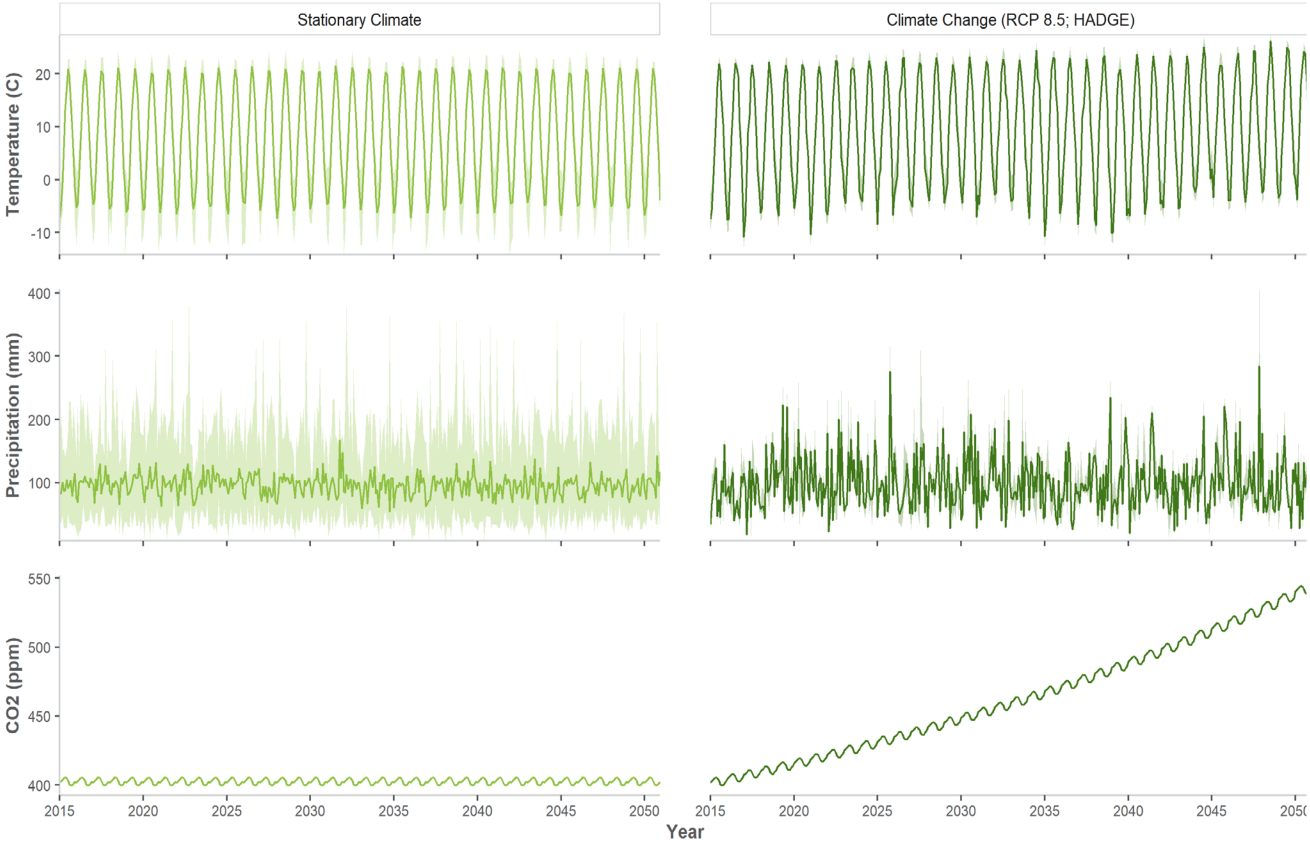
[59] Aber et al., “Predicting the Effects of Climate Change on Water Yield and Forest Production in the Northeastern United States.,” *Climate Research* 5 (1995): 207–22.

[60] Scheller, “LANDIS-II Biomass Community Output v2.0 Extension User Guide,” 2020, 0–4.

[61] US Environmental Protection Agency, “Level IV Ecoregions of Massachusetts,” *U.S.EPA Office of Research and Development (ORD) - National Health and Environmental Effects Research Laboratory (NHEERL)*, 2012.

based on the Soil Survey Geographic (SSURGO) database for Massachusetts, [62] following methods described in Thompson et al.[63] Future climatic conditions (e.g., monthly temperature and precipitation) and atmospheric CO$_2$ concentrations were based on the IPCC's Representative Concentration Pathway 8.5, as projected by the Hadley Global Environment Model v2 (HADGE). Ecoregion-scale climate values were estimated by summarizing the 12-km monthly downscaled projections of maximum and minimum temperature, precipitation, and associated CO$_2$ levels obtained from the USGS Geo Data Portal (Figure 6).[64] See Duveneck and Thompson [65] for detailed methodology. Belowground carbon (i.e., root biomass) was estimated during post-processing of LANDIS outputs as 25% of total aboveground carbon on each forested cell, based on Finzi et al.[66] The data used to initialize the LANDIS/PnET forest growth model are from c. 2015 (and earlier), which necessitated a 5-year simulation period to match the other data at 2020. Because there are stochastic elements in these models, the initial 2020 starting conditions reported are very similar, but not identical across all scenarios.

Figure 6. Massachusetts modeled climate showing median monthly temperature, precipitation, and CO$_2$ for the stationary climate and climate change climate within ecoregions in MA. The shaded areas for temperature and precipitation indicate minimum and maximum ecoregion values for the month as used in the LANDIS simulations.



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[62] Soil Survey Staff, "Gridded Soil Survey Geographic (GSSURGO) Database for Massachusetts," 2015.

[63] Thompson et al., "The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts"

[64] Stoner et al., "An Asynchronous Regional Regression Model for Statistical Downscaling of Daily Climate Variables," *International Journal of Climatology* 33, no. 11 (2013): 2473–94.

[65] Duveneck and Thompson, "Climate Change Imposes Phenological Trade-Offs on Forest Net Primary Productivity."

[66] Finzi et al., "The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change."

Small-scale natural disturbance was simulated in LANDIS/PnET using the Base Wind v.3.0 module.[67] [68] Base Wind simulates wind events utilizing user-defined sizes and wind rotation period for each climate-soil region. Users also define the wind severity classes and probability of damage, when a wind event occurs. The wind rotation period was set to 400-years and wind events ranged from one to 400-ha. The probability of tree mortality during a wind event increased with the age of the tree cohort and the wind intensity (Table 1).

The initial forest condition within LANDIS/PnET —in terms of tree species, age cohorts, and their initial carbon density—was initialized based on a gradient nearest neighbor imputation of US Forest Service Inventory and Analysis (FIA) plots.[69] [70] For each FIA plot used in the initial condition map, the total plot-level aboveground carbon was partitioned into broad tree species-by-age bins and then scaled to the 30-meter pixel-size. Because the model simulates tree species cohorts, it does not account for tree form or timber grade. The initial forest conditions include the 32 most common tree species in Massachusetts. The species' life history traits required by the model were derived from the literature [71] [72] [73] and refined during calibration (See Appendix Tables A1 & A2).

LANDIS/PnET has undergone extensive sensitivity analyses, calibration, and validation for New England forests.[74] [75] [76] [77] [78] [79] [80] To evaluate the specific parameterization used in this study, observed growth within FIA plots in Massachusetts were compared to simulated growth. The comparison only included FIA plots that were: fully forested, had multiple measurements after the year 2000, and had no recorded tree removal or major disturbance. All aboveground live tree C was included in the carbon estimates. Growth in aboveground carbon from all qualifying plots was annualized by calculating the change in carbon between measurements then dividing by the number of years between survey periods. The LANDIS data was calculated from a

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[67] Scheller and Mladenoff, "A Forest Growth and Biomass Module for a Landscape Simulation Model, LANDIS: Design, Validation, and Application," *Ecological Modelling* 180, no. 1 (2004): 211–29.

[68] Scheller and Domingo, "LANDIS-II Base Wind v3.0 Extension User Guide," 2020, 0–11.

[69] Duveneck, Thompson, and Wilson, "An Imputed Forest Composition Map for New England Screened by Species Range Boundaries," *Forest Ecology and Management* 347 (2015): 107–15.

[70] Because this imputation relied on FIA plots measured from 2008 to 2012, the estimated initial carbon density in the study is lower than would be estimated from a more contemporaneous measurement. However, these represent the best available data suitable for this type of modeling. To partially mitigate this bias, forest growth in LANDIS/PnET included a 5-year spin-up nominally representing the period spanning 2015 to 2020 to synchronize the timing with other datasets. See section 3.3.

[71] Liang et al., "How Disturbance, Competition, and Dispersal Interact to Prevent Tree Range Boundaries from Keeping Pace with Climate Change," *Global Change Biology* 24, no. 1 (2018): e335–51.

[72] McKenzie et al., "Local and Global Parameter Sensitivity within an Ecophysiologically Based Forest Landscape Model," *Environmental Modelling and Software* 117 (2019): 1–13.

[73] Thompson et al., "The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts"

[74] Thompson et al., "Four Land-Use Scenarios and Their Consequences for Forest Ecosystems and Services They Provide," *Ecosphere* 7, no. October (2016): 1–22.

[75] Duveneck and Thompson, "Climate Change Imposes Phenological Trade-Offs on Forest Net Primary Productivity."

[76] Liang et al., "How Disturbance, Competition, and Dispersal Interact to Prevent Tree Range Boundaries from Keeping Pace with Climate Change."

[77] Duveneck and Thompson, "Social and Biophysical Determinants of Future Forest Conditions in New England: Effects of a Modern Land-Use Regime," 2019.

[78] McKenzie et al., "Local and Global Parameter Sensitivity within an Ecophysiologically Based Forest Landscape Model."

[79] Duveneck et al., "Recovery Dynamics and Climate Change Effects to Future New England Forests."

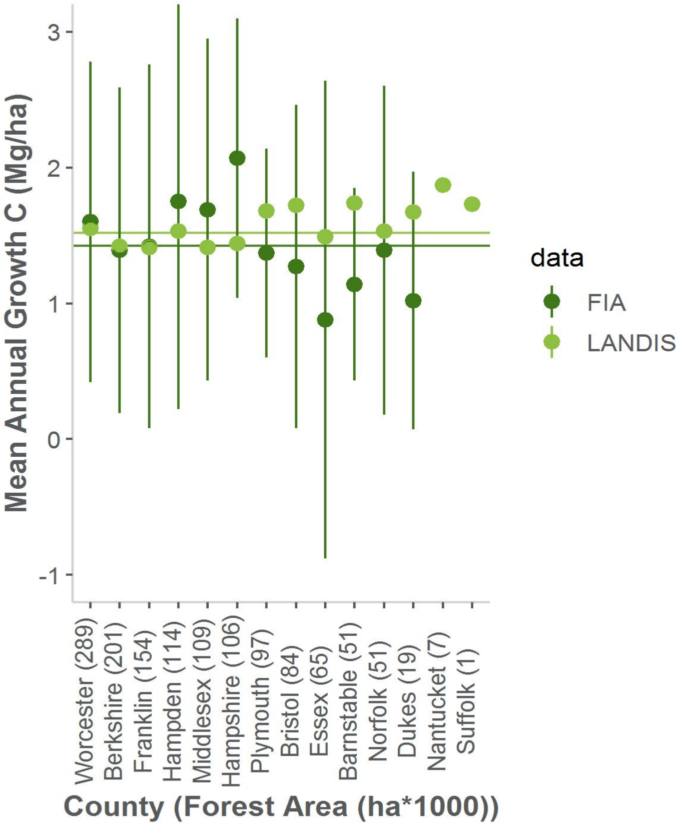
[80] Thompson et al., "The Influence of Land Use and Climate Change on Forest Biomass and Composition in Massachusetts, USA."

simulation with no harvest nor land cover change and where forest growth annualized by dividing the total carbon accumulated by the years between LANDIS outputs (i.e., five). The mean and standard deviation (FIA data only) of annual growth were summarized and compared for each Massachusetts county (Figure 7).

Table 1. Wind severity table for the LANDIS Wind Extension. Input table specifies the relationship between wind intensity and cohort mortality.[81]

Wind Severity	Relative Cohort Age (as a % age of species longevity)	Wind Mortality Probability
5	0% to 20%	0.05
4	20% to 50%	0.1
3	50% to 70%	0.3
2	70% to 85%	0.5
1	85% to 100%	0.65

*Figure 7. Comparison of mean annual growth between FIA and LANDIS data. Forest growth in the LANDIS model was validated by comparing to county-level mean annual growth with FIA county-level plot data growth over similar time periods for FIA plots that were: fully forested, had multiple measurements after the year 2000, and had no recorded tree removal or major disturbance. (Note: Realized net ecosystem productivity will include natural disturbance and mortality and, thus, be lower than these estimates). Error bars are one standard deviation of mean FIA plot growth. Horizontal dark green line is the mean annual FIA growth (1.42) and horizontal lighter green line is the pixel-level mean annual LANDIS growth (1.52). There are no forested FIA plots in Suffolk or Nantucket Counties. Counties are sorted in rank order by area of forest, which is given in parenthesis as ha * 1000.*



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[81] Scheller and Domingo, "LANDIS-II Base Wind v3.0 Extension User Guide."

3.4 Land-cover Change

The study estimated impacts of future land-cover change on terrestrial carbon stores. Recent trends in the observed patterns of land-cover change from 1990 to 2017 were used to parametrize a land-cover change model that simulated spatial patterns of future change. The cellular land-change model, Dinamica EGO v. 5.0 [82] was used to simulate geographic patterns of future land-cover change throughout the Commonwealth. Dinamica has been used previously to simulate land-cover change in New England. [83] [84] Dinamica is spatially explicit and capable of multi-scale stochastic simulations that incorporate spatial feedbacks. The model uses the weights-of-evidence (WoE) statistical method to calculate the transition probability for any given land-cover pixel. The WoE method uses a modified form of Bayes theorem of conditional probability [85] [86] to derive weights (W+) from a suite of spatial driver variables. W+ values were calculated independently for each transition and driver variable and then summed to create a composite transition probability map (Figure 8).[87] The highest W+ values in the composite probability map represent the sites with the greatest potential for transition using the combined predictive power of all driver variables. In this implementation of Dinamica, the spatial allocation of simulated land-cover transitions was calibrated to nine spatial driver variables shown to be associated with patterns of forest loss in New England (Table 2).[88] While cells within the Forest land-cover class accrued carbon with each timestep based on forest growth modeled within LANDIS/PnET (as described above), the non-forest land-cover classes were assigned unique carbon density estimates at each time step based on standard land-cover carbon densities assigned to each land-cover class. These non-forest land-cover carbon densities remained constant through time. See section 3.6 regarding Carbon Bookkeeping for details on carbon density estimates.

Observations of recent trends in land-cover change were derived from an annual time-series of 30-meter resolution land-cover maps spanning 1990 to 2017 and estimated using the Continuous Change Detection and Classification (CCDC) algorithm. The CCDC approach utilizes the full Landsat satellite record to identify changes in surface reflectance that are compared mathematically with ground-based observations to determine when land-cover change has occurred.[89] [90] The implementation of CCDC used here was initially developed for Mass

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[82] Soares-Filho, Rodrigues, and Costa, “Modeling Environmental Dynamics with Dinamica EGO,” 2009.

[83] Thompson et al., “Forest Loss in New England: A Projection of Recent Trends,” ed. Baldwin, *PLOS ONE* 12, no. 12 (2017): e0189636.

[84] Adams et al., “Simulating Forest Cover Change in the Northeastern U.S.: Decreasing Forest Area and Increasing Fragmentation,” *Landscape Ecology* 34, no. 10 (2019): 2401–19.

[85] Goodacre et al., “A Statistical Analysis of the Spatial Association of Seismicity with Drainage and Magnetic Anomalies in Western Quebec,” *Tectonophysics* 217, no. 03–04 (1993): 285–305.

[86] Bonham-Carter, Agterberg, and Wright, “Weights of Evidence Modelling: A New Approach to Mapping Mineral Potential,” in *Statistical Applications in the Earth Sciences: Geol.Survey Canada Paper*, 89th–9th ed., 1989, 171–83.

[87] Argemiro T. Leite-Filho et al., *Modeling Environmental Dynamics with Dinamica EGO*, ed. Filho, Filho, and Davis, 2.0 (Universidade Federal de Minas Gerais, 2020).

[88] Thorn, Thompson, and Plisinski, “Patterns and Predictors of Recent Forest Conversion in New England,” *Land* 5, no. 3 (2016): 1–17; Thompson et al., “Forest Loss in New England: A Projection of Recent Trends.”

[89] Zhu and Woodcock, “Continuous Change Detection and Classification of Land Cover Using All Available Landsat Data,” *Remote Sensing of Environment* 144 (2014): 152–71.

[90] Olofsson et al., “Time Series Analysis of Satellite Data Reveals Continuous Deforestation of New England since the 1980s,” *Environmental Research Letters* 11, no. 6 (2016).

Audubon's Losing Ground Sixth Edition report.[91] The fourteen original LULC classes used in Losing Ground were collapsed to five: Built, Forest, Pasture & Agriculture, Other, and Water (Figure 4). The six most prevalent transitions observed among these land-cover classes within the reference CCDC data were simulated. Figure 9 shows which parts of the Commonwealth experienced the most common type of land cover transition. The remaining transitions represented in the reference period were too infrequent to characterize statistically and were omitted from this study.

The rates of future development-induced land-cover change used in all scenarios were developed by EEA staff who conducted an analysis of historical land-cover demands generally falling within the Built class and parameterized by socioeconomic projections out to 2050. The socioeconomic forecasts, developed by the University of Massachusetts Donahue Institute (UMDI) and the Metropolitan Area Planning Council (MAPC), for the Massachusetts Department of Transportation's (MassDOT) Long-Range Transportation Plan (LRTP) included projections of population, households, and employment by municipality at decadal time-steps to 2040.[92] MAPC and EEA contracted for UMDI to extend these projections to 2050 as part of their MetroCommons 2050 planning effort and this report, respectively. UMDI and MAPC developed three different growth scenarios (baseline, high-growth, and low-growth); only the baseline and high-growth scenarios were evaluated in this study.

Mining the MAPC Land Parcel Database (built from the MassGIS Level 3 Parcel Geodatabase and other sources), a statewide repository of detailed land-use parcel data collected at the municipal level for property tax assessments, EEA staff computed average building characteristics for multiple housing typologies by community cohort.[93] These characteristics include an estimated mix of housing stock (e.g., X% single-family, Y% small multi-family, Z% large multifamily) constructed since 2000, and were used to parse the housing projections from UMDI into estimates of new housing stock. In addition, EEA staff applied average size coefficients for each typology and community cohort to estimate the total square footage that a development would represent. Rather than developing a more complex methodology utilizing employment projections, project team members elected to compute average ratios of commercial square footage to residential square footage, by community cohort, in order to project commercial build-out as a function of expected residential square footage.

EEA staff estimated future development by extrapolating estimates of square footage of new buildings into area of new development. To estimate infill (i.e., redevelopment of previously developed parcels), EEA staff summed negative changes in built land-cover classes (I.e., acreage losses of built classes, reflecting redevelopment within the built environment) in the MassGIS McConnel Land-Cover Database by community

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[91] Pasquarella and Holden, "Losing Ground 6, Annual Land Cover Products for Massachusetts." DOI: 10.5281/ZENODO.3531893

[92] Commonwealth of Massachusetts, "Socio-Economic Projections for 2020 Regional Transportation Plans." https://www.mass.gov/lists/socio-economic-projections-for-2020-regional-transportation-plans

[93] "Community cohorts" reflect the permutations of the 13 RPAs and five "community types" assigned semi-quantitatively to each of the 351 cities and towns in MA by MAPC. These types include:
1. Inner Core (MAPC region only); 2. Maturing Suburbs; 3. Developing Suburbs; 4. Regional Urban Centers; 5. Rural Towns
Not all permutations are represented in Massachusetts – for example there are no rural towns in the MAPC region. This approach reduces sample bias from looking at individual cities and towns, but still allows for greater differentiation than rolling up to the region level alone (e.g., while both are in the Pioneer Valley, development in Springfield is likely quite different from development in Montague).

cohort and dividing through by total development in that cohort to reach an average redevelopment rate. This dataset also separates out types of built area, such as roads and power lines, which allows a further adjustment to account for incremental infrastructure needs sited externally to the privately-owned parcels reflected in the MassGIS database. To estimate the total new Built cover area, including the building footprint and the surrounding “halo” of cleared land demanded by each additional household, EEA staff joined the high resolution (i.e., 1-meter) MassGIS 2016 LULC Geodatabase to the parcel database, then compared the area of lawn and driveway to the built area in each parcel, and summarized the relationship between building typology and community cohort. These values represent the full development footprint, which were summed to the RPA level and passed to the Dinamica EGO model to determine the within-RPA spatial allocation of land-cover change. For each RPA, the rate of land-cover change to development was partitioned into the three transitions -- “Forest to Built”, “Pasture & Agriculture to Built,” and “Other to Built.” The ratio of transitions was based on the observed ratio within the historical CCDC reference period (Figure 10). Rates for all other land-cover transitions were linear projections of the rates observed in the 1990-2017 reference period (Table 3).

The year, 2020 is the nominal start date for reporting landcover change results. The Continuous Change Detections and Classification (CCDC) data used to initialize the land-cover change model are from 2017, which necessitated a 3-year initialization to 2020 to harmonize the start time across multiple processes.

In addition, transitions to the Built land-cover class were prohibited within protected land, as mapped by the New England Protected Open Space (POS) dataset maintained by Harvard Forest and Highstead.[94] Transitions to the “Pasture & Agriculture” cover class were restricted to lands designated as Prime Farm Soils, identified using the Farmland Classes (i.e., farmland of statewide importance, all areas are prime farmland, farmland of unique importance, and farmland of local importance) from the Gridded Soil Survey Geographic (gSSURGO) Database.[95]

To estimate the carbon impacts of loss and gain of Forest cover, Dinamica outputs were coupled to LANDIS-II using the LANDIS Land Use Change (LUC) v3.2 module.[96] LUC simulates forest dynamics resulting from land-cover change and requires the user to specify carbon impacts associated with each land-cover transition. A land-cover transition can result in: (*1*) partial forest removal, such as when Forest cover is converted to Built cover, (*2*) total aboveground carbon removal, such as when Forest cover is converted to Pasture & Agriculture cover, or (*3*) it can initiate forest regrowth such as when Pasture & Agriculture cover is converted to Forest cover.

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[94] Harvard Forest, “New England Protected Open Space,” 2020.

[95] Soil Survey Staff, “Gridded Soil Survey Geographic (GSSURGO) Database for Massachusetts.”

[96] Thompson et al., “A LANDIS-II Extension for Incorporating Land Use and Other Disturbances,” *Environmental Software and Modeling* 75 (2016): 202–5.

Figure 8. The probability of Forest cover converting to Built cover based on observed change in the reference period in relation to nine spatial predictor variables (Table 2). Probability values shown are only comparable within RPAs, which were parametrized independently i.e. High/Low values are not equivalent across the Commonwealth.

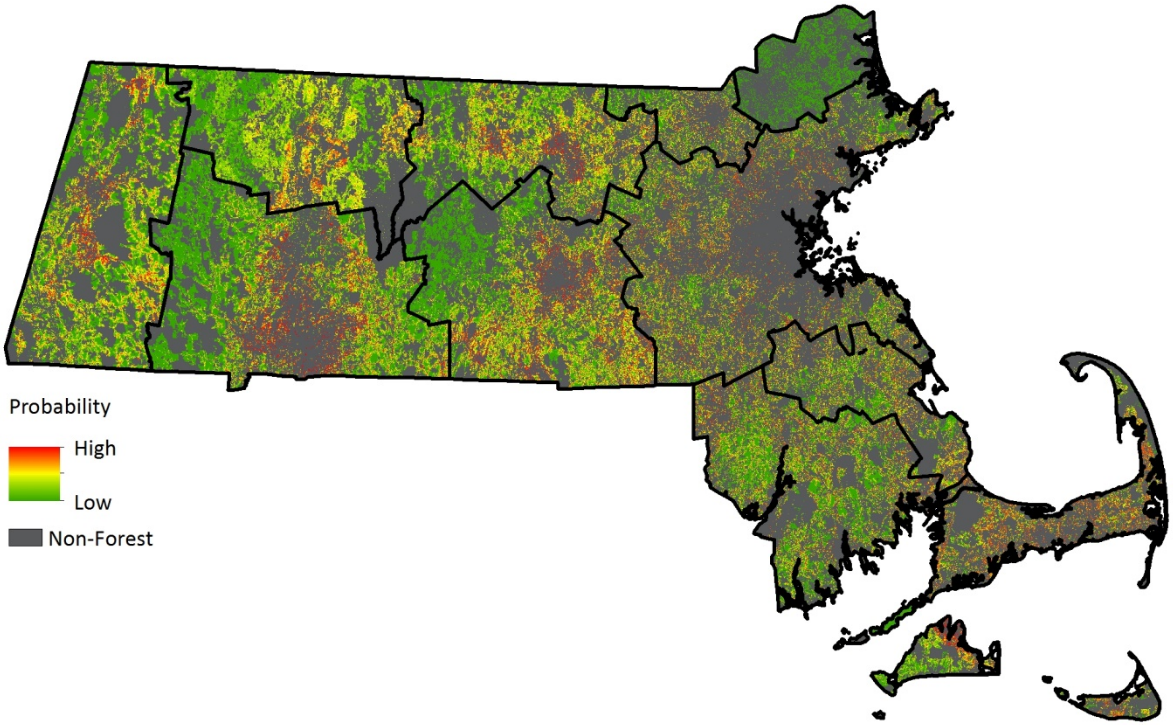

Table 2. Spatial driver variables used to parameterize the spatial allocation component of the Dinamica land-cover change models

Variable	Units	Min. Bin Size	Source
Distance to City Centers	Meters	5,000 m	U.S. Department of the Census 1990, 2010.
Population Density	People per Square Kilometer	25 ppl/sq. km.	U.S. Department of the Census 1990, 2010.
Distance to Roads/Highways	Meters	50 m	Olofsson et al. 2016
Distance to “Built”	Meters	50 m	Pasquarella and Holden 2019
Slope	Degrees	1°	U.S. Department of the Census 1990, 2010
Land Owner Type	Categorical	NA	MassGIS
Wetlands + Flood Zones	Categorical	NA	U.S. Fish and Wildlife Service 2016, Federal Emergency Management Agency 2016, United States Geological Service 2016.

Figure 9. This map shows the spatial distribution of the major transition types mapped by the CCDC algorithm from 1990 to 2017. Because individual transition patches are difficult to see at the Commonwealth scale, this abstraction assigns a transition type to all areas of Massachusetts based on the <u>*nearest*</u> *real transition patch. Quantities of change should not be inferred from this map.*

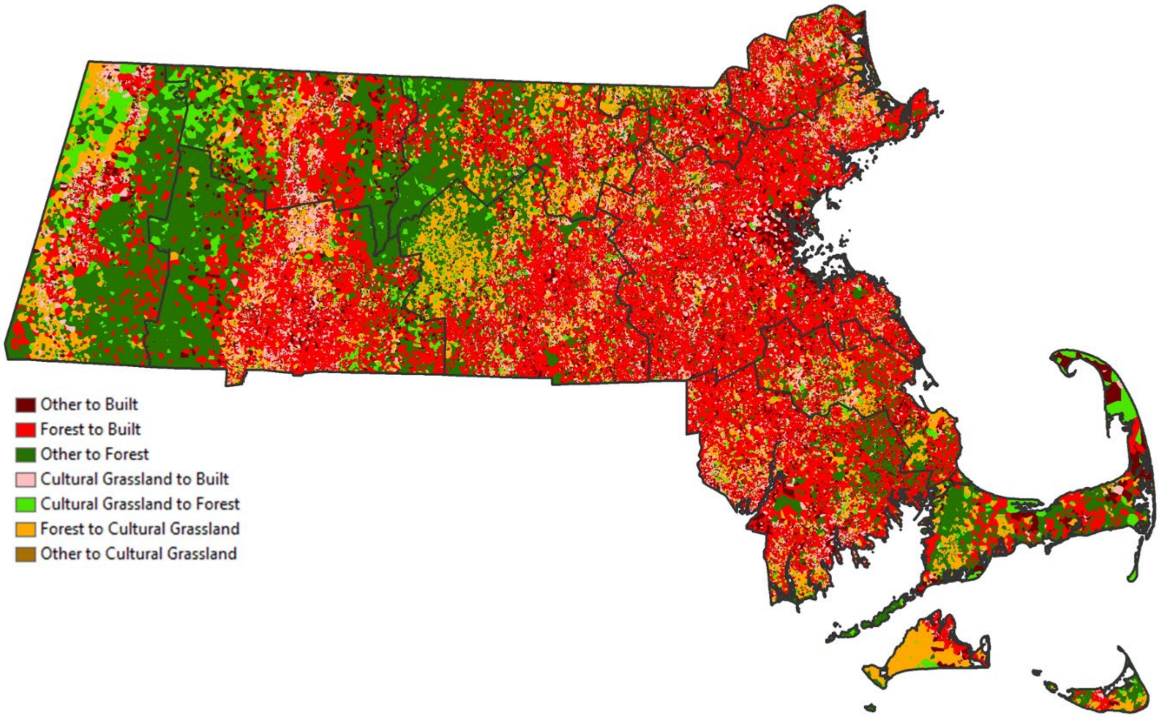

Figure 10. Land-cover type lost to Built in reference period. The size of each pie chart reflects the relative amount of change within the RPA.

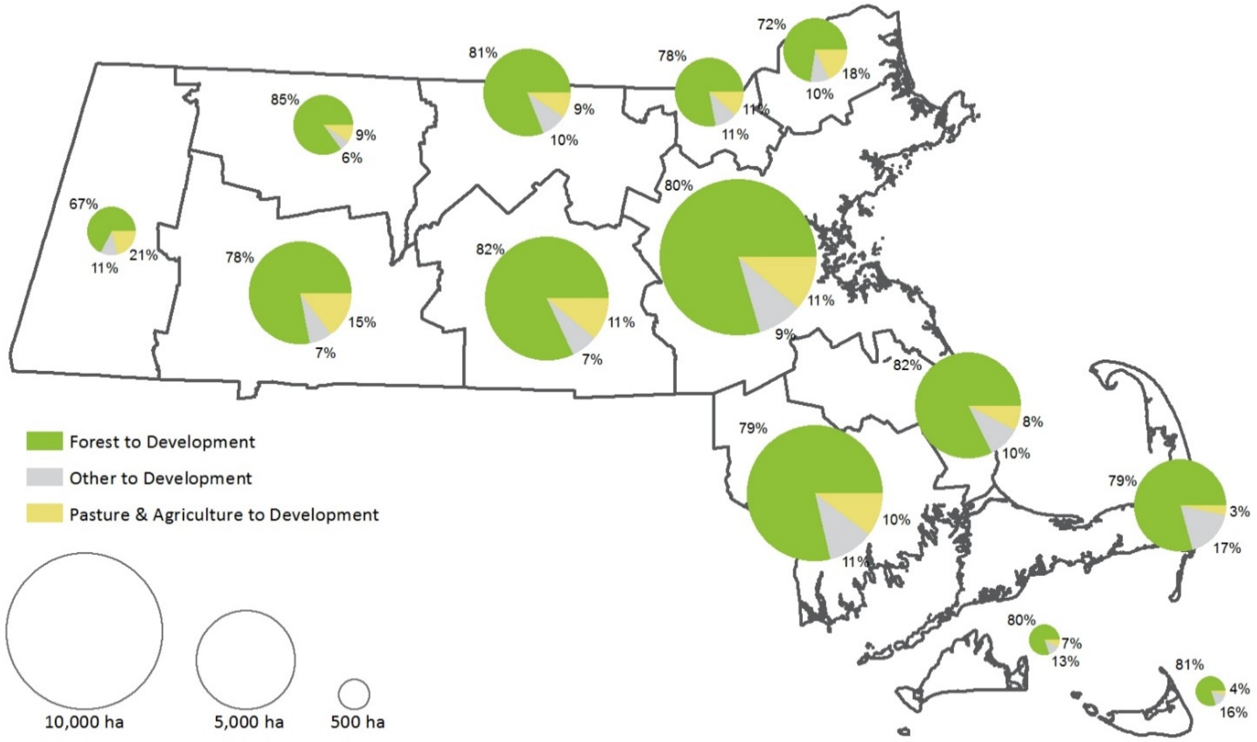

Table 3. Simulated land-cover transitions 2020-2050. The Baseline and Policy scenarios (BL_A, BL_{MV}, PR_A, and PR_{MV}) all have the same level of land-cover change, only the High Population Growth (HPG_A) scenario uses the High Population rates of change

Transitions 2020-2050	Baseline and Policy (ha)	High Population (ha)
Forest to Development	36,883	49,573
Forest to Pasture & Agriculture	8,221	8,203
Agriculture to Development	5,364	7,282
Agriculture to Forest	1,100	1,097
Other to Development	4,084	5,644
Other to Forest	4,917	4,916

3.5 Timber Harvesting

The study estimated the impacts of potential future commercial timber harvest regimes on terrestrial carbon. Commercial timber harvesting was modeled in LANDIS/PnET using the Biomass Harvest v.4.3 module,[97] 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 carbon allocation model (see below), and, in subsequent timesteps, the LANDIS/PnET growth model responds to any harvest-induced changes to the site's growing conditions (e.g., increased light availability and growing space).

Representatives from the Massachusetts Department of Conservation and Recreation's (DCR) Bureau of Forest Fire Control and Forestry worked with Harvard Forest scientists to develop the baseline harvest specifications and rates using Massachusetts forest cutting plan data (i.e., M.G.L. Chapter 132 Cutting Plans) submitted between July 1, 2001 and August 31, 2017. The Massachusetts Forest Cutting Practices Act requires a Cutting Plan when commercial timber harvest removals are anticipated to be greater than 25,000 board feet or 50 cords. Plans include property location, type of cutting proposed, and the estimated volume of wood that will be harvested. Although the dataset has limitations, including lack of standardized reporting and verification of harvested area or volume/mass, it is the best available data, and has been used previously to quantify Massachusetts' harvest regimes.[98] [99] For this study, the cutting plan data was used to develop the baseline harvest prescription (Table 4) and commercial harvest rates by RPA. Alternative prescriptions were developed based on the baseline prescriptions and future expectations. To represent a range of harvest sizes, each prescription had a large and small patch size variant. The smaller patch variant had a two hectare (ha) stand minimum and no prescription's harvest size exceeded 16 ha. The larger patch variant had a 10 ha stand minimum and no prescription's harvest size exceeded 57 ha. Within all simulations, commercial harvest was

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[97] Gustafson et al., "Spatial Simulation of Forest Succession and Timber Harvesting Using LANDIS," *Can. J. For. Res.* 30 (2000): 32–43.

[98] Kittredge et al., "Three Decades of Forest Harvesting along a Suburban-Rural Continuum," *Ecosphere* 8, no. 7 (2017): 1–22.

[99] McDonald et al., "Forest Harvesting and Land-Use Conversion over Two Decades in Massachusetts," *Forest Ecology and Management* 227, no. 1–2 (2006): 31–41.

excluded from areas where harvesting was known to be prohibited based on the New England Protected Open Space (POS) dataset.[100]

The Biomass Harvest module was also used to simulate incidental tree removals, such as non-commercial forestry, firewood cutting, or hazard tree removal. Attributes of incidental harvesting were based on Belair and Ducey's [101] analysis of FIA data in southern New England (MA, CT and RI). This analysis showed that incidental harvesting made up approximately 37% of all harvest events but removed a comparatively small proportion of stand biomass. Accordingly, 4,300 ha/yr of incidental harvest was added to the 7,360 ha/yr of commercial harvest and distributed evenly across the Commonwealth. Each incidental harvest removed approximately 6% of all species' biomass across all age classes on the affected sites. When reporting results, removals from incidental harvesting were not included with commercial forestry but were tracked separately as an additional contribution to carbon emissions.

Table 4. Harvest Prescription Specifications. General requirements for harvest prescriptions (Rx). Harvest Type Simulation = Baseline & Policy indicates those Rx are in all harvest simulations. Harvest Type Simulation = Baseline indicates the Rx are only in the baseline harvest simulations (BL_A,BL_{MV},HPG_A). Harvest Type Simulation = Policy indicates those Rx are only in the policy harvest simulations (PR_A, PR_{MV}). Rx Name is the general prescription name (of which there is a smaller and a larger patch size variant). Entry requirement columns dictate conditions for harvest to occur. Min. Age of Oldest Cohort – a stand must have at least one cohort of the target age. Min. Time Since Last Harvest- a stand must not have been harvested in at least the number of years listed. Min. Patch Size (ha) is the minimum stand size in ha, for a harvest to occur. % Low Value Species to Remove and% High Value Species to remove are the % ages set for each species as grouped by high and low economic value and age range. Age Range identifies cohort ages subject to removal. See Table A4 for Rx specifications.

		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**	**Age Range**
Baseline & Policy	Thin	50	15	2	28	50	30	AGE > 50
Baseline & Policy	OSR* High Intensity	100	15	2	57	100	100	20 < AGE < 100
						97	95	AGE > 100
Baseline & Policy	OSR* Low Intensity	100	15	2	40	90	90	20 < AGE < 100
						90	66	AGE > 100
Baseline & Policy	Uneven	100	50	2	30	50	50	20 < AGE < 50
						75	50	20 < AGE < 100
						75	75	AGE > 100
Baseline	High-grade	60	40	2	42	40	80	AGE > 60
Policy	Thin (EXR)**	50	15	2	28	50	30	AGE > 50
Policy	OSR* Low Intensity (EXR)**	150	15	2	40	90	90	20 < AGE < 100
						90	66	AGE > 100

*OSR overstory removal harvest- rotation ending silvicultural component of even-aged management

**(EXR) extended rotation harvest

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[100] Harvard Forest, "New England Protected Open Space," 2020.

[101] Belair and Ducey, "Patterns in Forest Harvesting in New England and New York: Using FIA Data to Evaluate Silvicultural Outcomes," *Journal of Forestry* 116, no. 3 (2018): 273–82.

3.6 Carbon Bookkeeping

Outputs from the LANDIS/PnET ecosystem model and the Dinamica land-cover change model were combined with a series of carbon density factors using a spatially explicit carbon bookkeeping approach. This approach tracks above- and belowground pools of terrestrial carbon for each land-cover class and calculates changes to carbon stocks and emissions associated with LULC change (Table 5).

Table 5. Carbon Densities and Land Cover Transitions. Note that belowground carbon refers to live root carbon and does not include soil organic carbon, which is described in Table 6.

Land-Cover Class	Aboveground Carbon Mg/ha	Belowground Carbon Mg/ha	Simulated transitions to:
Built (non-urban)	41.1	10.3	None
Built (low density)	26.9	6.7	None
Built (high density)	11.6	2.9	None
Forest	Ranges from 0 – 173	25% of Aboveground Carbon	Built, Pasture & Agriculture
Pasture & Agriculture	6.4	1.6	Built, Forest
Other (non-forested wetland)	1.9	0.5	Built, Forest
Other (saltwater wetland)	2.9	0.7	Built, Forest
Other (active cranberry bog)	1.9	0.5	Built, Forest
Other (man-made bare)	0	0	Built, Forest
Other (natural barren)	0	0	Built, Forest
Water	0	0	None

3.6.1 Carbon in the Forest Environment

Within the Forest cover class, total aboveground live carbon for each tree species-by-age cohort was a mapped output from LANDIS and reflected tree growth and mortality at each time step. Belowground carbon (i.e., root) was estimated as 25% of the total aboveground carbon. Soil organic carbon was estimated as 279.0 Mg/ha on all forested cells (Healthy Soils Action Plan). See section 3.7 below.

3.6.2 Carbon in the Built Environment

Relying on the Raciti et al.[102] study of carbon densities within developed areas in Massachusetts, the Built land-cover class was split into three levels of development intensity, each with their own carbon density: High Population, Low Population, and Non-urban. Land that was already developed in 2020 was delineated into these classes using Raciti et al.'s method of dasymetric interpolation of population density (US Census) and a moving window approach to mapping impervious surface area (NLCD) (Figure 11). Then, using the lower standard error bound for each class, the carbon density for each class was weighted based on the reported within-class proportion of residential vs. other development land use, resulting in carbon densities of 41.1

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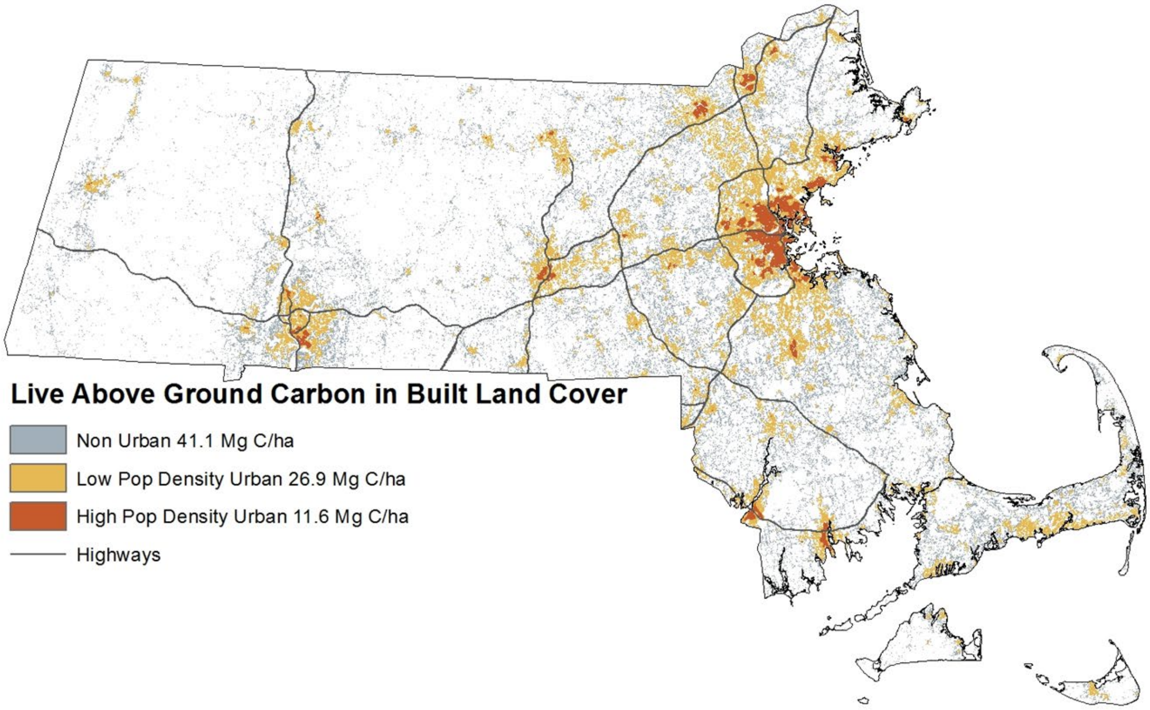
[102] Raciti et al., "Inconsistent Definitions of 'Urban' Result in Different Conclusions about the Size of Urban Carbon and Nitrogen Stocks," *Ecological Applications* 22, no. 3 (2012): 1015–35.

Mg/ha for Non-urban, 26.9 Mg/ha for Low Population Density Urban, and 11.6 Mg/ha for High Population Density Urban.

Figure 11. Live aboveground carbon in the Built land-cover class.



Within the carbon bookkeeping framework, when Forest cover was converted to Built cover, the site retained 29.2% of its pre-development forest live carbon density (above- and below-ground). This estimate was again based on Raciti et al.[103] who compared carbon density in built environments to carbon densities of adjacent forests. Raciti et al.[104] reported mean aboveground carbon density of 116 Mg/ha for Forests, 41 Mg/ha for Residential, and 16 Mg/ha for Other Developed. An area-weighted average of the Residential and Other Developed classes produces a mean carbon density of 34 Mg/ha for the combined Residential + Other Developed class, which is 29.2% of the carbon compared to neighboring Forests. Carbon densities within all Built classes were held static throughout the simulations.

3.6.3 Land-cover Type Carbon Density

Carbon densities for other land-cover classes were provided by EEA's Technical Steering Committee for the Decarbonization Roadmap Study (Table A3). Values for pasture (6.9 Mg/ha) and hayfield (6.2 Mg/ha) were averaged to derive a value for Pasture & Agriculture of 6.5 Mg/ha. The composite Other class was decomposed into its five constituent CCDC classes. Values for Saltwater Wetland and Non-Forest Wetland were given as 2.9 and 1.9 Mg/ha, Cranberry Bogs were assumed to have aboveground carbon densities similar to Wetlands (1.9 Mg/ha), and Barren-Natural and Barren-Man-Made were assumed to have zero aboveground carbon.

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[103] Raciti et al.

[104] Raciti et al.

Whenever a cell underwent a transition from one of these minor land-cover classes, its aboveground carbon was updated to reflect the new land-cover class.

3.6.4 The Fate of Removed Carbon

The fate of carbon removed from the Forest class—either during commercial or incidental harvest or when converted to Built—was tracked using a common method of carbon accounting, often referred to as the revised 1605(b) program or methodology, which in its original form was published in section 1605(b) of the Energy Policy Act of 1992. These methods were developed and then updated by the US Forest Service[105] for the EPA's greenhouse gas accounting framework. These methods were then adapted for the LANDIS/PnET framework for both aboveground and belowground (i.e., root) carbon. This approach allocates harvested tree carbon to different pools—e.g., slash, landfill, firewood, and wood products—according to forest type and species-specific decay or transfer rates (Figure 12). While the Smith et al.[106] carbon accounting methods are based on relatively older timber product output reports and mill efficiencies etc., the methods are both standard and flexible enough that they could be modified to use with the cohort modeling approach of LANDIS and updated as new information is developed.

The Smith et al. (2006)[107] carbon accounting methods for aboveground harvested carbon uses individual tree measures (e.g., diameter, merchantability) to define growing stock. Here, the approach was modified to accommodate the tree cohort outputs from the LANDIS/PnET framework, which do not have individual tree measures, and applied to the cohorts removed through either commercial or incidental harvest (tracked separately). Instead of using individual tree measures to define growing stock, LANDIS/PnET cohorts 20 years old or older were considered potential growing stock. For removed cohorts less than 20 years old, 14% of the total carbon was allocated to the slash pool, following Reinmann et al.,[108] to account for material left on site to decay, and the remaining 86% of the harvested carbon was allocated to the fuelwood category and was mineralized (emitted) by the next time step, 5 years later (Figure 12). Then, for all removed cohorts over 20 years old, or the potential growing stock, the same 14% was allocated to the slash pool to account for material left on site to decay (which may include some unmerchantable removed wood), with the remaining 86% of the removed cohorts considered growing stock. The removed growing stock C was allocated to different carbon pools at each time step using the modified Smith et al., (2006)[109] accounting methods (illustrated in Figure 12) based on the forest type and wood type of the removed cohorts. The carbon pools estimated at each time step of the model run include:

- emitted through decomposition or combustion,
- emitted with energy recapture (e.g., used in energy generation),

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[105] Smith et al., "United States Department of Agriculture Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States," 2006.

[106] Smith et al.

[107] Smith et al.

[108] Reinmann et al., "Assessing the Global Warming Potential of Human Settlement Expansion in a Mesic Temperate Landscape from 2005 to 2050," *Science of The Total Environment* 545–546 (2016): 512–24.

[109] Smith et al., "United States Department of Agriculture Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States."

- still in use (e.g., in wood products such as building material),
- landfilled, and
- still in slash or root (not decomposed yet).

We only tracked the carbon impacted by commercial and incidental harvest or conversion during our model runs from 2020-2050; therefore, any carbon stored or emitted as a result of harvesting or conversion previous to 2020 was not included in our accounting.

Estimating these final carbon pools required several steps of partitioning the carbon from the removed cohorts into different types of timber used in production based on forest and wood types. Therefore, at each time step, the forested pixels were reclassified by species' biomass dominance into the "Forest Types" defined in Smith et al. (2006), from the LANDIS-II Output Biomass Reclass[110] and the Biomass Community Output[111] extensions outputs. While these Forest Types were defined based on FIA forest types, we modified the definitions of these forest types slightly to fit our LANDIS-II outputs of species cohort biomass dominance. Then, the removed aboveground growing stock carbon (after slash removal) was partitioned into saw timber and pole timber using the forest type and hardwood/softwood specific values of the sawtimber fraction from Smith et al., (2006; Table 4)[112]. Next, the saw timber and pole timber wood type-specific ratios of industrial roundwood to roundwood volume and the bark to wood from Smith et al., (2006; Table 5)[113] were used to partition the saw timber and pole timber into saw log, pulp wood, bark and fuel wood. Finally, transition rates from Smith et al. (2006)[114] were used to allocate the removed wood from the saw log, pulp wood, bark, and fuel wood to the final tracked carbon pools (in gray in Figure 12) by time since removal.

Similarly, decay rates for slash[115] and harvested tree roots[116] were used to allocate these components of the harvested wood to the final tracked carbon pools for each time step, so that each component moved from their pool at time of removal to emissions based on time since removal. For example, as time since harvest passes, the amount of the total removed carbon that is "root" decreases while the amount that is "emitted" increases. Additionally, forest carbon removed for development did not enter the timber market but was mineralized (emitted) in the time step of development.[117]

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[110] Scheller and Domingo, "LANDIS-II Biomass Reclass Output v1.0 Extension User Guide," 2006.

[111] Scheller, "LANDIS-II Biomass Community Output v2.0 Extension User Guide."

[112] Smith et al., "United States Department of Agriculture Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States."

[113] Smith et al.

[114] Tang et al., "Estimating Potential Forest NPP, Biomass and Their Climatic Sensitivity in New England Using a Dynamic Ecosystem Model," *Ecosphere* 1, no. 6 (2010).

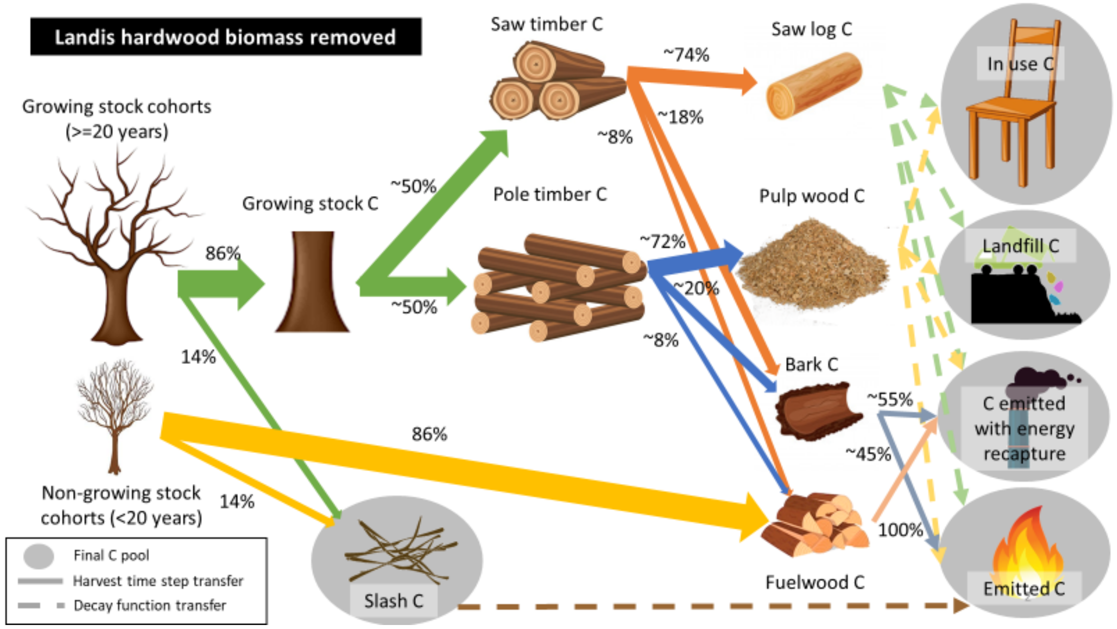
[115] Russell et al., "Residence Times and Decay Rates of Downed Woody Debris Biomass/Carbon in Eastern US Forests," *Ecosystems* 17, no. 5 (2014): 765–77.

[116] Zhang and Wang, "The Decomposition of Fine and Coarse Roots: Their Global Patterns and Controlling Factors," *Scientific Reports* 5 (2015): 1–10.

[117] There is little research documenting the fate of trees removed during land clearing, see. To the extent that some removed trees enter timber markets, this assumption will overestimate emissions from development. Wienert, "From Forestland To House Lot : Carbon Stock Changes and Greenhouse Gas Emissions from Exurban Land Development in Cnetral New Hampshire" (Brown University, 2006). [2] Porder, Lipson, and Harrison, "Carbon Stock Changes in Soil and Aboveground Biomass from House Lot Development in King County, Washington, USA," *Open Journal of Forestry* 02, no. 01 (2012): 1–8.

[1]

Figure 12. Post-Harvest Carbon Allocation. An example of the harvested carbon allocation process for hardwood species removed in the LANDIS simulations. Pools that are summed and tracked at each time step have a grey background. Solid arrows represent a transfer from one pool to the next at the time of harvest, while dashed lines represent carbon transfer proportions that depend on the time since harvest (which is why a % is not given for these lines).



3.7 Soil Organic Carbon

The bulk of the analyses in this report considers live carbon, mostly trees, and the fate of harvested wood. The emphasis on live carbon neglects soil organic carbon, which constitutes at least half of the terrestrial carbon pool in Massachusetts. Unfortunately, scientific understanding of soil carbon and its response to LULC change lags far behind the understanding of live tree carbon; therefore, conducting a mechanistically-based analysis was not possible for this study. Instead, this report leverages a recent analysis of soil carbon as part of the Massachusetts Healthy Soils Action Plan.[118] That plan reanalyzed data from the USDA Natural Resource Conservation Service's Rapid Carbon Assessment Program[119] to develop soil carbon densities for drainage classes and land-cover types in the Commonwealth. Their findings suggest that soil carbon may be a much larger pool than previous studies suggest. The Healthy Soils data were used here to establish an initial estimate of the potential impacts of the LULC scenarios on soil carbon stocks. Soil carbon emissions were estimated using a "gain- loss approach" in which emissions were estimated by multiplying the area of land in each land-cover class by the soil carbon density estimate from the Healthy Soils team. This approach assumes that commercial forestry has no impact on soil carbon, because forestry does not cause a land-cover transition. However, the effects of forestry on soil carbon are variable and depend on the time of year and care taken during harvesting.[120] This assumption likely underestimates the impact of commercial forestry.

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[118] Regenerative Design Group, "News - Massachusetts Healthy soils action plan: Updates." https://www.regenerativedesigngroup.com/healthy-soils-action-plan/

[119] West, L, S Wills, and T Loecke. "Rapid Carbon Assessment (RaCA) Methodology," 2013, 9.

[120] Nave et al., "Harvest Impacts on Soil Carbon Storage in Temperate Forests," *Forest Ecology and Management* 259, no. 5 (2010): 857–66.

Soil Organic Carbon (SOC) densities were estimated to a depth of 1m and were mapped onto a 3m resolution High Resolution Land-cover dataset by the Healthy Soils Action Plan 2020 Team. For this LULC change study, the 3m map was overlain onto the 30m CCDC-derived land-cover map and the mean carbon densities from the Healthy Soils map were cross-walked onto the five CCDC land-cover classes (Table 6). The largest discrepancy between the classification schemes used by Healthy Soils and CCDC was that Healthy Soils contain separate Forest and Forested Wetland classes, whereas CCDC contains only a single composite Forest class. Using an area-weighted average within a land-cover class, SOC densities for each cell were kept static so long as no land-cover transitions occurred. When a transition did occur, SOC densities were updated to reflect the new land-cover class.

Table 6. Soil Organic Carbon densities for each CCDC Land-cover class, derived from the Healthy Soils Action Plan estimates. These estimates were derived from a spatial overlay of the land cover classes used here with those used by the Health Soils Action Plan team. Because of the differences in the number and alignment of the land cover categories, there is not complete alignment between the estimates at the class level, but overall Commonwealth estimates are the same.

CCDC Land-cover	Mean SOC (Mg/ha)
Built	94.6
Forest	279.0
Pasture & Agriculture	122.4
Water	0.0
Saltwater Wetland (Other)	343.7
Active Cranberry Bog (Other)	111.5
Non-Forest Wetland (Other)	575.8
Barren Natural (Other)	109.8
Barren Man-made (Other)	103.0

3.8 Land-use Scenarios

Five land-use scenarios were developed in consultation with EEA and DCR then evaluated in terms of their potential impact on terrestrial carbon and carbon emissions. Each land-use scenario included the same parameterizations for climate change, natural disturbance, and incidental harvesting, described above. Scenarios differed in terms of their rates of development and the rates and types of commercial forestry. Controls on the spatial allocation of development and forestry were the same for all scenarios and were based on patterns observed in the recent past.

3.8.1 Baseline with Regulated Harvest Area (BL_A)

In this scenario, the rate of new development was linked to population projections produced by UMDI and MAPC, consistent with MassDOT's regional transportation planning process,[121] which assumes a continuation of the high rate of growth seen in the previous ten years, driven, primarily, by high levels of net migration, especially international in-migration. This is followed by a return to a longer-term historical average in migration-related growth rates after 2030. By 2050, net population growth is relatively decelerated by

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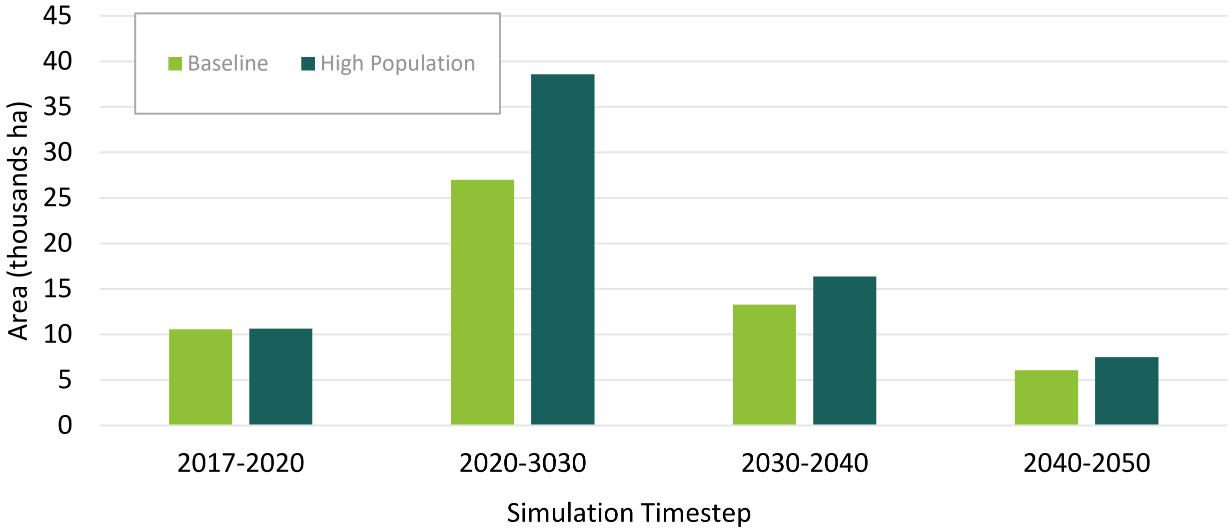
[121] Strate et al., "Massachusetts Population Projections by Regional Planning Area Massachusetts Population Projections by Regional Planning Area," 2018.

demographic trends (e.g., relatively low birth rates and the actuarial decline of baby boomers). The scenario resulted in 46,331 ha of new development (i.e., Built cover) by 2050 (see Methods 3.3). Rates of new development generally decrease over time, spanning a high of 2,700 ha/yr to low of 606 ha/yr (Figure 13). The MAPC and CMRPC have the highest rates of development due to the projected population increases around Boston and Worcester, respectively. Overall, new development extends westward from the I-495 corridor (Figure 14). The lowest rates of new development were on the Cape and Islands (CCC, MVC, & NPEDC) and the Berkshires (BRPC). Within each RPA, new development replaced Forest cover and Pasture & Agriculture cover at a ratio that corresponded to the ratio observed during the reference period. Similarly, the within RPA spatial pattern of new development followed the spatial patterns observed during the reference period, with distance to Built cover and distance to roads serving as the most important spatial predictor variables.

The targeted forest area subject to commercial timber harvest was set to 7,360 ha/yr, which was the average annual (non-salvage) harvested area reported in the Cutting Plan data during the 2001 to 2017 reference period. The area harvested in each timestep was allocated among RPAs based on the average proportion observed during the reference period (Table 7), such that much more area was harvested in the western RPAs. Five different harvest prescriptions were simulated (Table 4). The prescriptions varied in terms of the harvest patch size, minimum age of the oldest cohort in the stand, the species and ages of removed cohorts, and the proportion of species' biomass removed. The ratio of prescriptions within RPAs was based on the reference period and held constant across RPAs and through time. Sites were selected for harvest based on forest characteristics using the LANDIS/Biomass Harvest extension, without regard to ownership.[122]

Figure 13. Area converted to Built land cover per decade in the scenarios. The 2017-2020 timestep is considered a "spin up" timestep in order to bring the scenarios land cover maps up to present day.



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[122] Areas where the New England Protected Open Space database indicated that commercial harvest is prohibited were excluded.

Figure 14. Development Rates by RPA in the Baseline scenarios

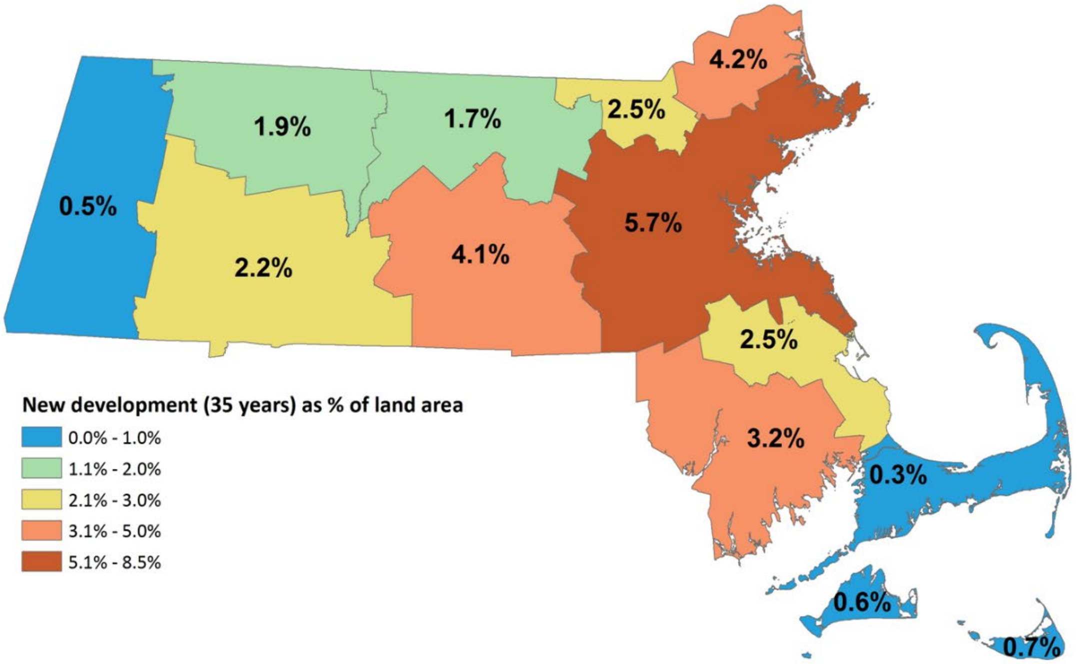


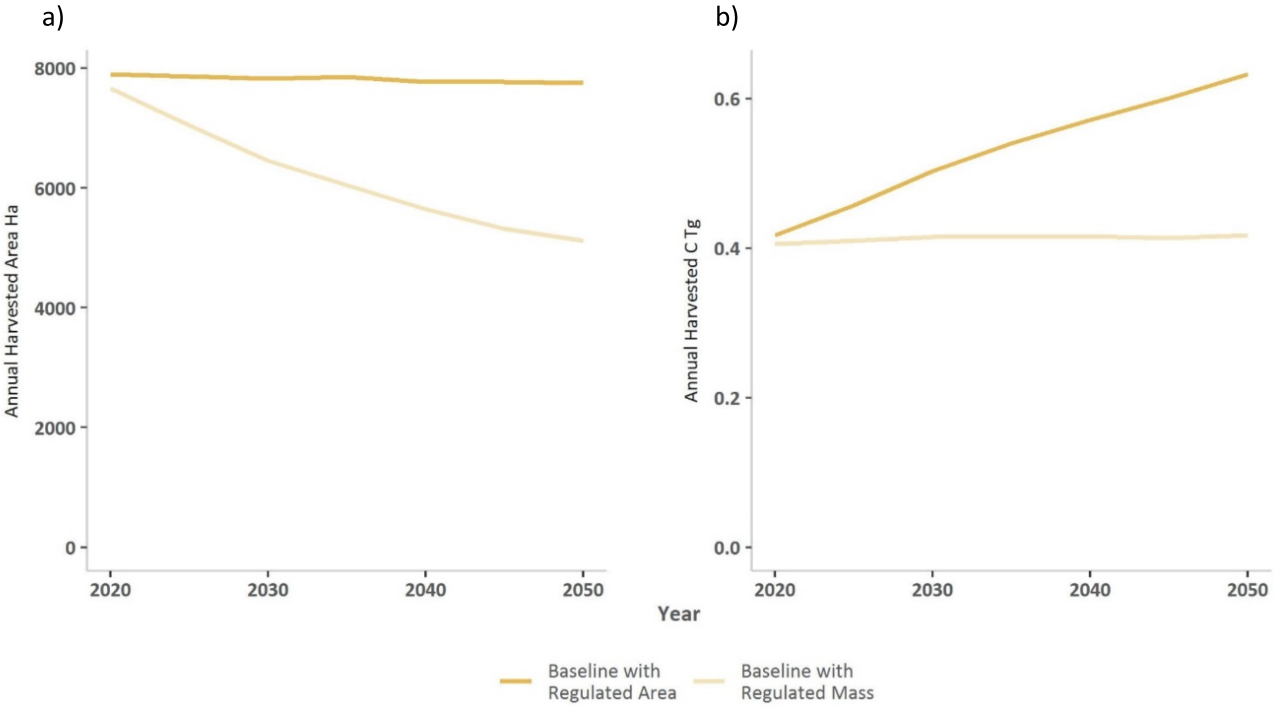
Table 7. Target area to harvest for the Baseline with Regulated Harvest Area (BL_A) Simulation. Landis Biomass Harvest Extension targeted annual area to harvest (ha), as calculated from MA Forest Cutting Plan data. The area of treatment/prescription was divided equally into a small and large patch size variant. Prescription names described in Table A4.

	Prescription					
RPA	**Thin**	**OSR High Intensity**	**OSR Low Intensity**	**Uneven**	**High-grade**	**Total**
BRPC	148.5	84.7	212.8	597.8	192.1	1236.0
CCC	1.5	12.9	0.5	0.2	4.9	20.0
CMRPC	189.5	120.9	396.3	367.9	83.0	1158.0
FRCOG	273.2	108.4	420.2	734.4	137.5	1674.0
MAPC	32.1	18.8	96.2	113.8	12.6	273.0
MRPC	115.2	73.5	248.2	233.9	50.6	721.0
MVC	0.0	1.1	0.1	0.0	1.4	3.0
MVPC	4.0	1.4	4.9	10.2	0.4	21.0
NMCOG	5.2	3.3	23.2	27.4	2.6	62.0
NPEDC	0.0	0.0	0.0	0.0	0.0	0.0
OCPC	6.0	4.9	9.6	16.0	0.8	37.0
PVPC	279.5	144.0	398.7	986.9	274.1	2083.0
SRPEDD	9.8	9.2	14.8	36.1	2.6	73.0
Total	1064.5	583.0	1825.4	3124.5	762.7	7360.0

3.8.2 Baseline with Regulated Harvest Mass/Volume (BL_{MV})

Simulated development rates and patterns in the BL_{MV} scenario were identical to BL_A scenario described above**.** The BL_{MV} differs from the BL_A in that the harvested mass/volume is held constant as opposed to the harvest area. To accommodate forest growth while maintaining a constant level of harvested biomass, the harvested area in the BL_{MV} scenario declines over time. Harvested biomass and area in the BL_{MV} approximates the BL_A scenario in the first timestep—7,661 ha/yr and 0.41 Tg C/yr (1.5 MMT of CO_2eq; Figure 15). Harvested area in the BL_{MV} declined to approximately 5,100 ha/yr by 2050. Harvests were removed at random from the BL_A scenario to achieve the target harvest biomass, while maintaining the proportions of prescriptions and relative allocation across RPAs.

Figure 15. Difference between Baseline with Regulated Harvest Area (BL_A) and Baseline with Regulated Harvest Mass/Volume runs (BL_{MV}). a) Shows difference in area between harvest drivers. b) Shows difference in Tg C between harvest drivers. The initial harvest values from BL_A set the target harvest mass for BL_{MV} simulation by holding the mass of harvested trees steady over the length of the simulation, reducing the area harvested.



3.8.3 Policy Run with Regulated Harvest Area (PR_A)

Simulated development rates and patterns in the PR_A scenario were identical to the BL_A scenario described above**.** The PR_A scenario envisions changes that improve silviculture practices and markets. Changes to silviculture, implemented over a rapid timeframe, included: (1) an elimination of high-grading; (2) an increase in the minimum forest age requirement for the overstory removal component of the lower-intensity even-age management system to model extended rotations; and (3) a shift in the area harvested from higher-intensity removals to lower-intensity removals to model increased structural retention (Table 8). The prescriptions were designed such that the overall amount of sawlog biomass harvested at the beginning of the modeled temporal span would be held constant relative to recent trends, under the assumption that the harvest of sawlogs was the primary driver of harvest activity, and to mitigate the possibility of leakage due to policy-induced shifts in harvest practices. Thus, additional area was harvested to realize a similar volume of biomass harvested as in the Baseline Scenario, but under less-intensive harvest removals.

Changes to markets envisioned new demand for harvested wood as might be expected if there were a cross-laminated timber and/or cellulose insulation production facility located within a procurement radius that intersected Massachusetts. Demand for biomass of certain softwood species and tree classes was envisioned and simulated. Area harvested to meet that demand was assumed to be additional to the area harvested in the baseline harvest simulation and proportional to the predominance of those species and tree grades harvested in recent trends. The additional area harvested was approximately 20% of the area harvested in recent trends (Table 7).

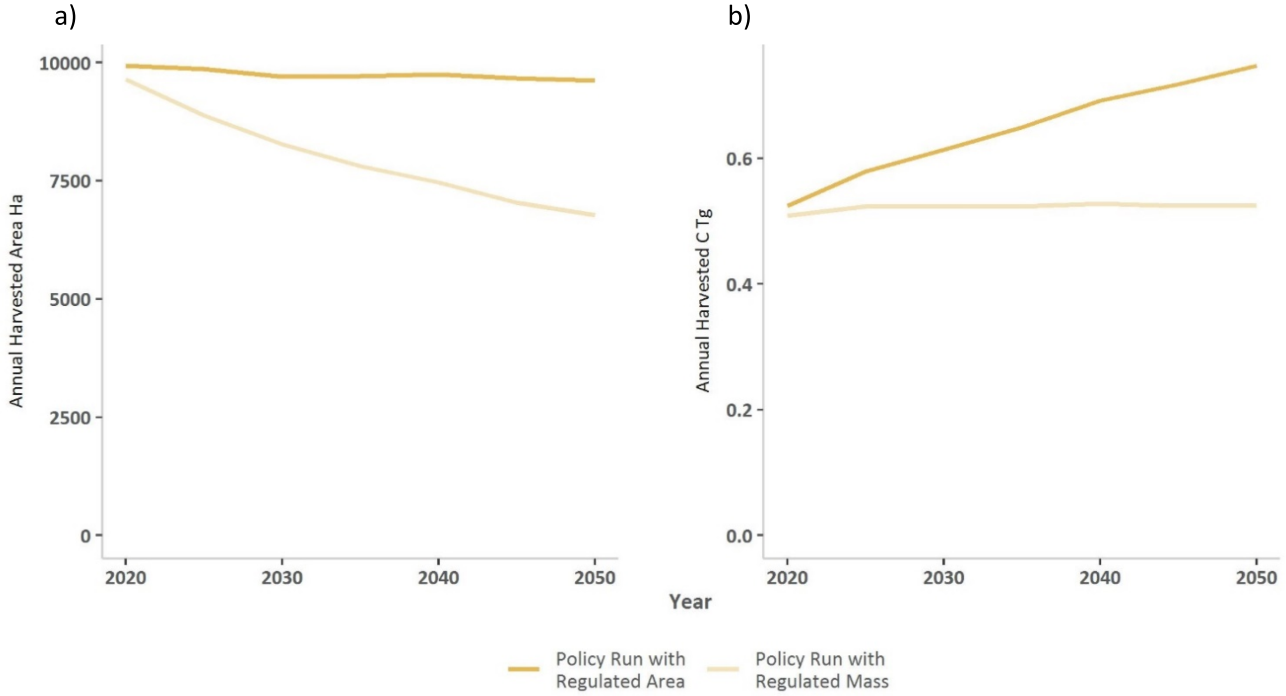
Table 8. Target area to harvest for the Policy Run with Regulated Harvest Area (PR_A) Simulation. Landis Biomass Harvest Extension targeted annual area to harvest (ha), estimated and scaled from MA Forest Cutting Plan data. The area of treatment/prescription was divided equally into a small and large patch size variant. Prescription names described in Table A4.

	Prescription						
RPA	**Thin**	**OSR High Intensity**	**OSR Low Intensity**	**Uneven**	**OSR Low Intensity (EXR)**	**Thin (EXR)**	**Total**
BRPC	79.4	22.3	94.0	875.3	282.0	238.4	1591.3
CCC	0.6	3.4	2.5	14.0	7.4	1.9	29.8
CMRPC	76.4	31.8	151.7	574.6	455.0	229.1	1518.5
FRCOG	109.6	28.5	159.4	1033.1	478.2	328.6	2137.3
MAPC	11.7	4.9	34.5	160.5	103.4	35.2	350.3
MRPC	44.2	19.3	92.8	355.2	278.3	132.6	922.4
MVC	0.0	0.3	0.5	0.0	1.5	0.0	2.2
MVPC	1.3	0.4	1.7	13.7	5.2	3.9	26.3
NMCOG	2.2	0.8	7.7	36.0	23.1	6.6	76.4
NPEDC	0	0	0	0	0	0	0
OCPC	2.0	1.3	3.8	24.2	11.4	6.0	48.7
PVPC	134.9	37.9	168.7	1421.5	506.1	404.7	2673.9
SRPEDD	3.6	2.4	5.7	50.0	17.0	10.9	89.6
Total	466.0	153.3	722.8	4558.1	2168.4	1398.1	9466.7

3.8.4 Policy Run with Regulated Harvest Mass/Volume (PR_{MV})

Simulated development rates and patterns in the PR_{MV} scenario were identical to the BL_{MV} scenario described above**.** The PR_{MV} scenario methodology replicates the BL_{MV} methodology, where the harvested mass/volume is held constant as opposed to the harvest area. To accommodate forest growth while maintaining a constant level of harvested biomass, the harvested area in the PR_{MV} scenario declines over time. Harvested biomass and area in the PR_{MV} approximates the PR_A scenario in the first timestep — 9,646 ha/yr and 0.51 Tg C/yr (1.9 MMT of CO_2eq; Figure 16). To maintain a constant mass/volume, the harvested area in the PR_{MV} declined to approximately 6,800 ha/yr by 2050. Harvests were removed at random from the PR_A scenario to achieve the target harvest biomass, while maintaining the proportions of prescriptions and relative allocation across RPAs.

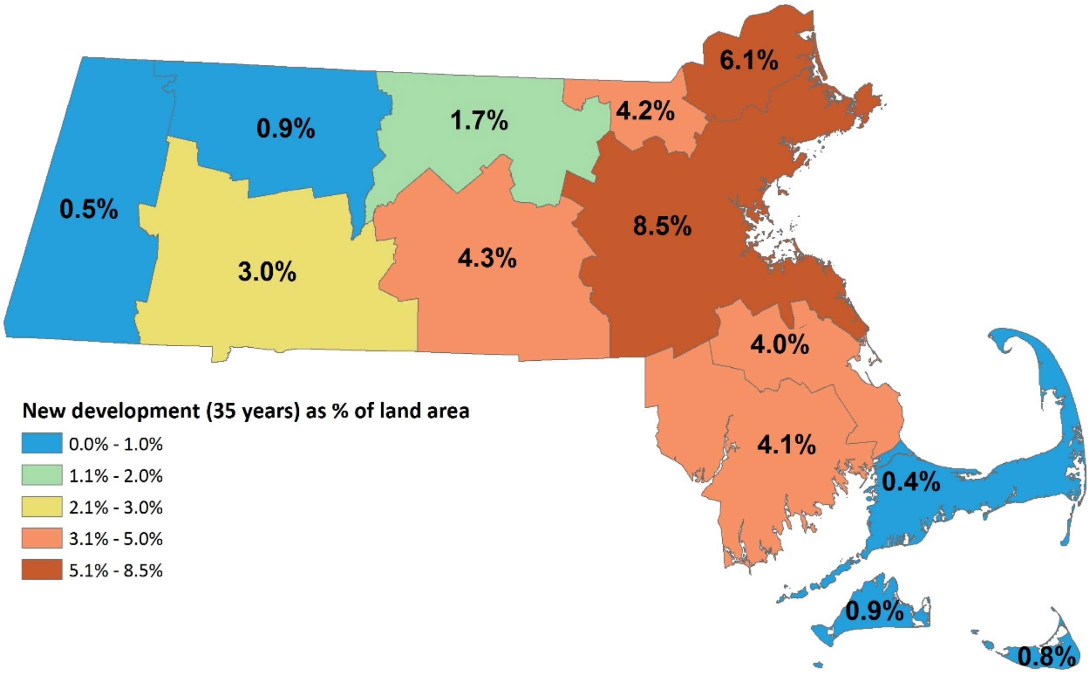
Figure 16. Difference Between Policy Run with Regulated Harvest Area (PR_A) and Policy Run with Regulated Harvest Mass/Volume (PR_{MV}) Runs. a) Shows difference in area between harvest drivers. b) Shows difference in Tg C between harvest drivers. The initial harvest values from PR_A simulation set the target harvest mass for the PR_{MV} simulation by holding the mass of harvested trees steady over the length of the simulation, reducing the area harvested.



3.8.5 High Population Growth with Regulated Harvest Area (HP_A)

In this scenario, the rate of new development is linked to a high population projection produced by MAPC and UMDI, which assumes longer continuation of the net in-migration responsible for most of the population growth in the baseline scenario. Total growth still decelerates, however, because even high higher net migration rates cannot completely wash out expected demographic and actuarial trends. The total area of new development during the 30-year simulation period is 62,499 ha, 34.9% higher than the baseline runs. New development generally decreases over time spanning a high of 3,860 ha/yr to low of 752 ha/yr at the Commonwealth scale (Figure 13). The proportion of new development is distributed across RPAs similarly to the Baseline runs, with most new development occurring along the I-495 corridor (Figure 17). Just as with the Baseline runs, within RPA patterns emulate observed development in the reference period. Simulated commercial forestry rates and patterns in the High Population Growth scenario were identical to the BL_A scenario described above**.**

Figure 17. Development Rates by RPA in the High Population Growth scenario



4 Results

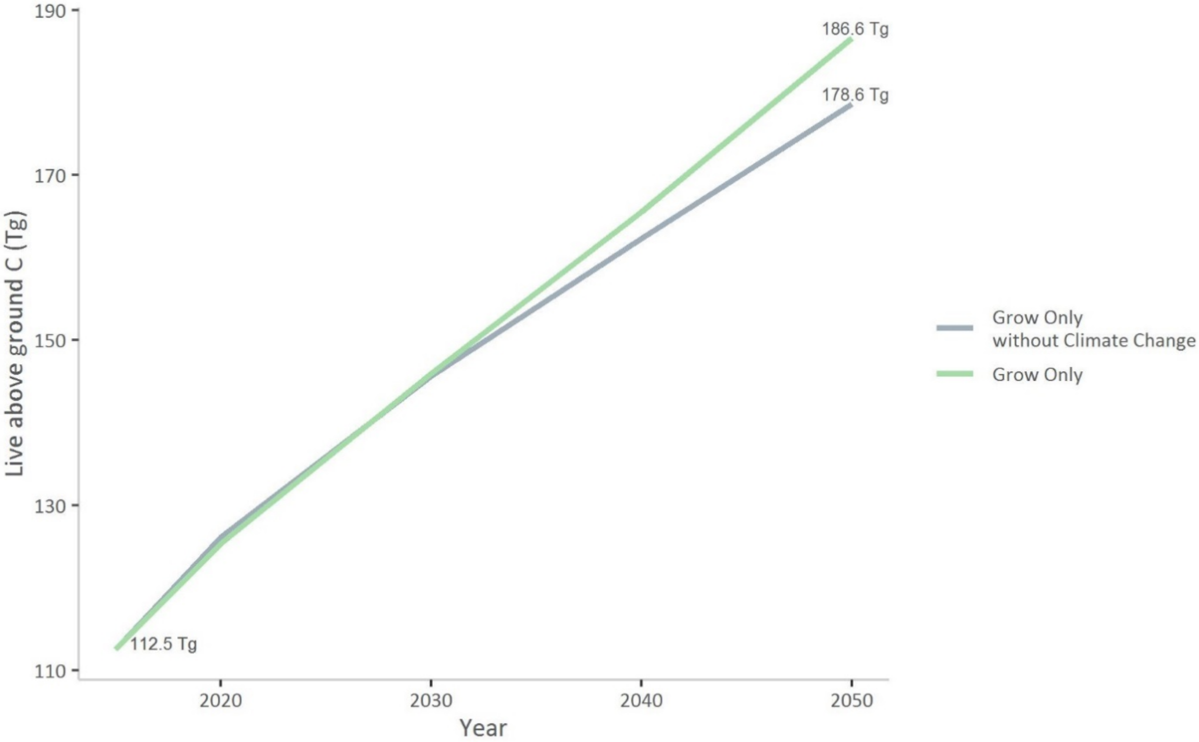
4.1 Forest Ecosystem Processes –Impacts on terrestrial carbon

In 2020, at the start of the simulations, there is approximately 123 Tg of live carbon in Massachusetts (Table 9). Most of the carbon is in forests (~84%). The state-wide average net ecosystem production (NEP; i.e., the rate of aboveground carbon sequestration) at the onset of the simulations, within undisturbed forests, averaged 1.52 Mg/ha/yr (5.6 MT of CO_2eq). At the RPA scale, average NEP ranged from 1.37 to 1.87 Mg/ha/yr (5.0 to 6.9 MT of CO_2eq, respectively). Simulated aboveground NEP compared favorably with estimates based on U.S. Forest Service field inventory plots (Figure 7), which averaged 1.42 Mg/ha/yr (5.2 MMT of CO_2eq) for the Commonwealth. Climate change and the associated increases in atmospheric CO_2 increased the rate of forest growth in the simulations, which resulted in a 7.96 Tg (29.2 MMT of CO_2eq) increase in total terrestrial carbon stores as compared to a simulation that excluded the effects of climate change (Figure 18). The effects of climate change and CO_2 were not apparent in the simulations until after the year 2030.

Table 9. State-wide and forest-only carbon stocks in 2020 and 2050. Live C 2020 Tg is the net landscape-scale (includes all land cover types) C stock in 2020. Live C 2050 Tg is the net landscape-scale carbon stock in 2050. Live Growth 2020-2050 C Tg is the difference in C stocks between 2050 and 2020. % Increase is the% increase in C over the simulation. Live Forest C 2020 Tg is the C stock in the net forest land cover type in 2020. Live Forest C 2050 Tg is the C stock in the net forest land cover type in 2050. The last two columns show the change in% forest cover the length of the simulation.

Scenario	Live C 2020 Tg	Live C 2050 Tg	Total Live Growth (2020 – 2050) C Tg	% Increase	Live Forest C 2020 Tg	Live Forest C 2050 Tg	% of C in Forest 2020	% of C in Forest 2050
Baseline with Regulated Area (BL_A)	122.86	168.86	45.99	37.44	103.02	147.98	83.85	87.63
Baseline with Constant Mass/Volume (BL_{MV})	122.98	171.04	48.05	39.07	103.14	150.16	83.87	87.79
Policy Run with Constant Area (PR_A)	122.53	167.43	44.90	36.64	102.69	146.56	83.81	87.54
Policy Run with Constant Mass/Volume (PR_{MV})	122.47	169.87	47.40	38.70	102.63	149.00	83.80	87.71
High Population Growth with Constant Area (HP_A)	122.86	167.75	44.89	36.53	103.02	146.56	83.85	87.37

Figure 18. Change in landscape live carbon stocks (Tg) within two reference simulations, one that includes changes in temperature, precipitation and CO₂ concentrations associated with the 8.5 RCP climate change scenario, and one that maintains the current climate and CO₂ concentrations. Neither simulation includes LULC change. This figure includes five years of growth (2015 – 2020) used to initialize the model see section 3.3 for details.



4.2 LULC Scenario Impacts on Terrestrial Carbon

Differences in harvest area and harvested carbon explained much of the differences among the scenarios (Figure 19; Table 10). However, forest growth was, by far, the primary driver of change in terrestrial carbon stocks and, overall, there was only modest differences among scenarios (Figure 20).

Figure 19: Annual harvested area and carbon removed at the beginning (2020) and the end of the simulation (2050).

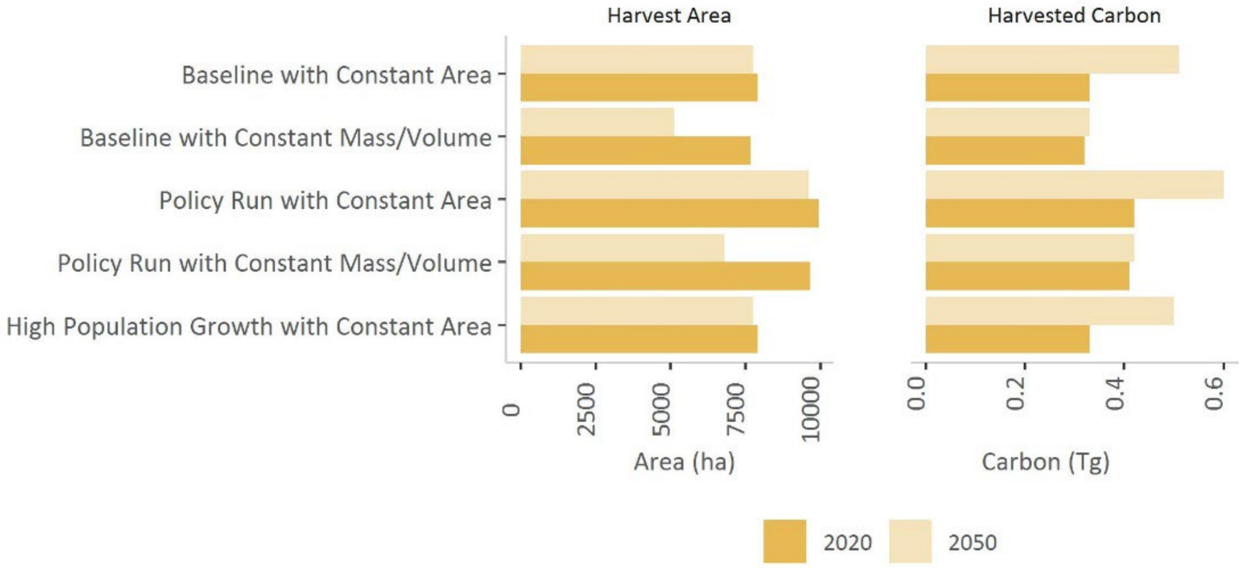
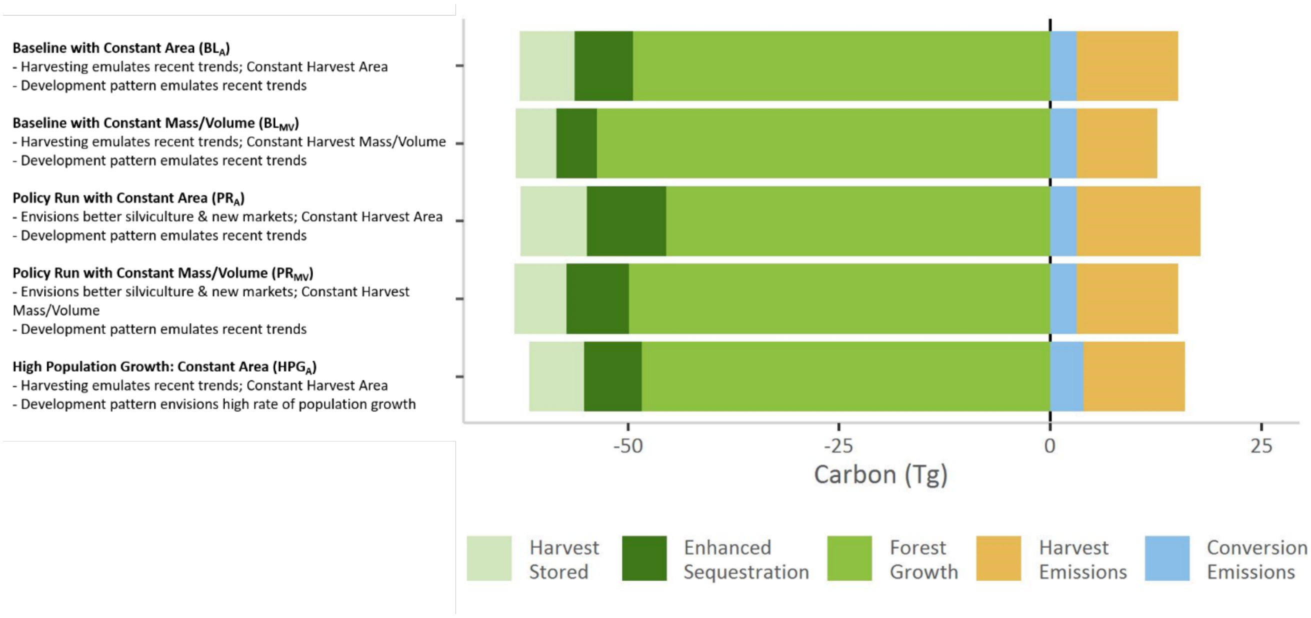


Table 10. Year 2050 carbon stocks and LULC change effects for each scenario. Live C is the carbon stock (Tg) on the landscape; Remaining values show the effect of the flux in Tg. Positive numbers indicate emissions and negative numbers indicate sequestration or stored C pools. Afforestation Effect is the C increase relative to a simulation that did not allow afforestation. Incidental Effect is the emissions associated with incidental tree removal. Direct Development Effect is the development-related emissions from removed tree and root carbon; Secondary Development Effect is the forgone sequestration- the difference in carbon stocks between simulation with and without development minus the development-related emissions; Harvested carbon is the total carbon removed on the landscape by harvest; Harvested In Use is the carbon in long-lived wood products; Harvested Stored is the material remaining and yet to be decomposed (i.e., slash or roots) or in a landfill; Direct Forestry Effect is the Harvested carbon minus the Harvested Stored; Secondary Forestry Effect is the difference in carbon stocks between a simulation with or without harvest minus the harvest-related emissions. Total Direct LULC Effect are the direct effects of development, harvest, and incidental removal. Total LULC Effect Tg is the carbon storage impact, which quantifies the combined impacts of development and forestry on carbon storage in 2050.

	Baseline with Constant Area	Baseline with Constant Mass/Volume	Policy Run with Constant Area	Policy Run with Constant Mass/Volume	High Population Growth with Constant Area
		STOCKS			
Live C in 2050	168.86	171.03	167.44	169.88	167.75
		FLUXES			
Afforestation Effect	-0.07	-0.07	-0.07	-0.07	-0.07
Incidental Effect	0.80	0.80	0.78	0.79	0.78
Direct Development Effect	3.11	3.12	3.10	3.11	3.93
Secondary Development Effect	2.15	2.14	2.16	2.15	2.50
Harvested	18.62	14.41	22.61	18.18	18.56
Harvested In Use	-3.31	-2.43	-3.98	-3.06	-3.29
Harvested Stored	-3.22	-2.42	-3.89	-3.05	-3.21
Direct Forestry Effect	12.09	9.56	14.74	12.07	12.06
Secondary Forestry Effect	-6.87	-4.83	-9.41	-7.43	-6.85
Total Direct LULC Effect	16.00	13.48	18.62	15.97	16.77
Total LULC Effect	11.28	10.79	11.37	10.69	12.42

Figure 20. Simulated changes in terrestrial carbon stocks between 2020 and 2050 as affected by five alternative land-use scenario overview and impact on live carbon and emissions by year 2050.



4.2.1 Baseline with Constant Harvest Area (BL_A) Scenario

Aggregate changes in live carbon stocks

In the BL_A scenario, forest growth increased total live carbon in Massachusetts to 168.86 Tg (+37.4%; 619.7 MMT of CO_2eq) by the year 2050 (Table 10). Between 2020 and 2050, development and commercial forestry removed 21.71 Tg of live carbon (79.7 MMT of CO_2eq; Figure 21). Of that removed carbon, 3.31 Tg C was stored in wood products and 3.22 Tg C remained on the landscape either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Therefore, the total direct emissions associated with LULC change (i.e., commercial forestry, incidental harvesting, and development) in this scenario was 16.0 Tg C (58.7 MMT of CO_2eq). Afforestation increased live carbon by 0.07 Tg. In addition, LULC change impacted terrestrial carbon stores via its impacts on ecosystem dynamics. Specifically, an estimated 2.15 Tg (7.9 MMT of CO_2eq) of carbon sequestration was forgone by converting forests to development. Forestry enhanced rates of sequestration, which increased carbon stocks by 6.87 Tg. Accounting for all these factors, the net impact of LULC change in the BL_A scenario was a 11.28 Tg (41.4 MMT of CO_2eq) reduction in carbon by the year 2050 (Table 10) compared to a counterfactual scenario with no LULC change.

Impacts of development on live carbon stocks

The BL_A scenario included 46,331 ha of new built landcover, including 45,104 ha of forest loss (Table 3). The highest concentration of new development was around the I-95 and I-495 highway corridors, with less dense development around Worcester and the Connecticut River Valley (Figure 22). Development reduced live carbon stocks by 5.26 Tg (direct effect + secondary effect; 19.3 MMT of CO_2eq) (Table 10) relative to a counterfactual scenario with no LULC change. Of that, 59% were direct emissions caused by the clearing of trees and 41% were secondary storage loss due to the forgone carbon sequestration in those sites through 2050.

Figure 21. Comparison of the allocation of carbon removed during development, commercial forestry, and incidental harvesting from 2020 to 2050 across all simulations. Pools with values below zero are stored C, while pools above zero are emissions.

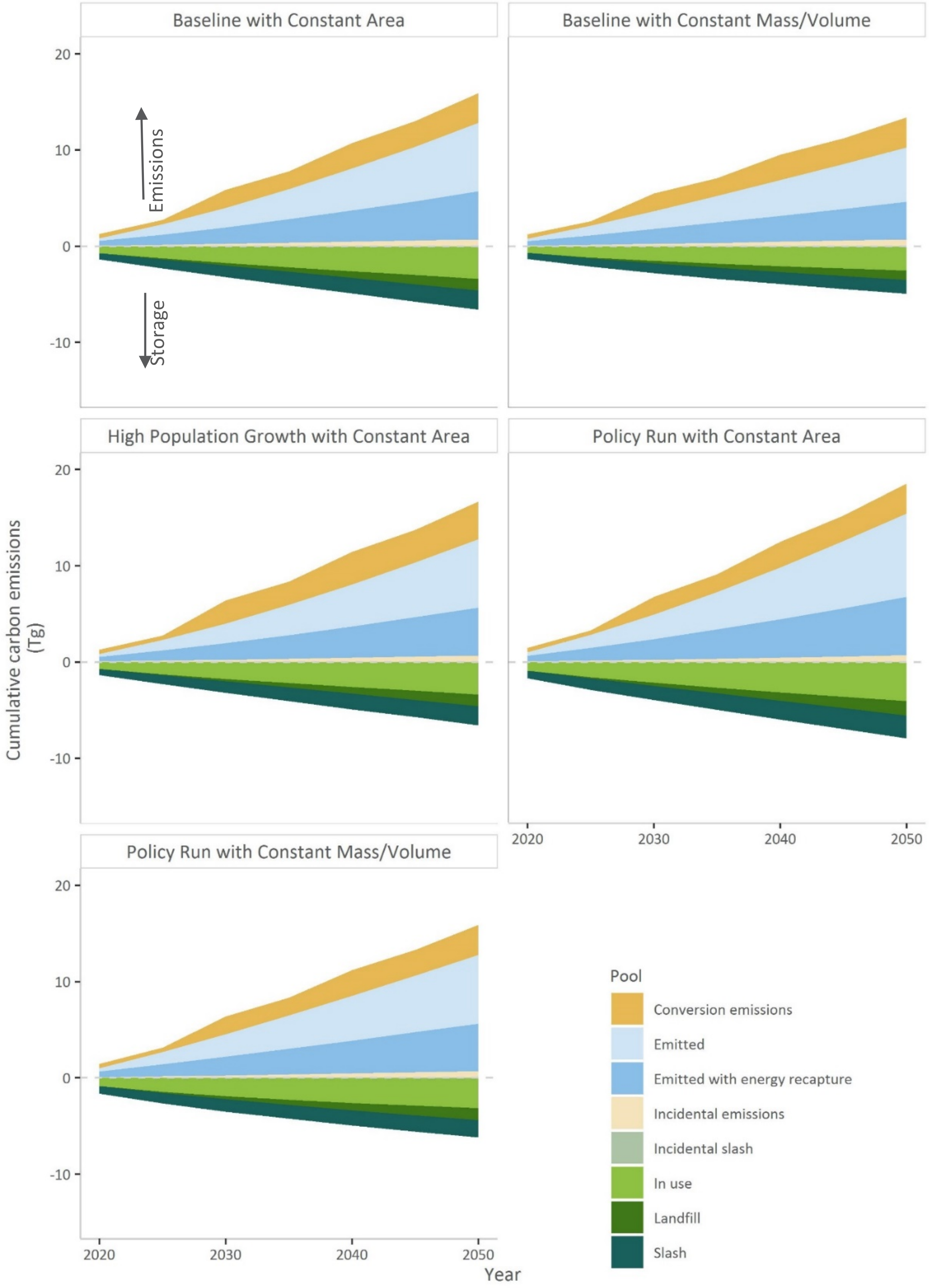
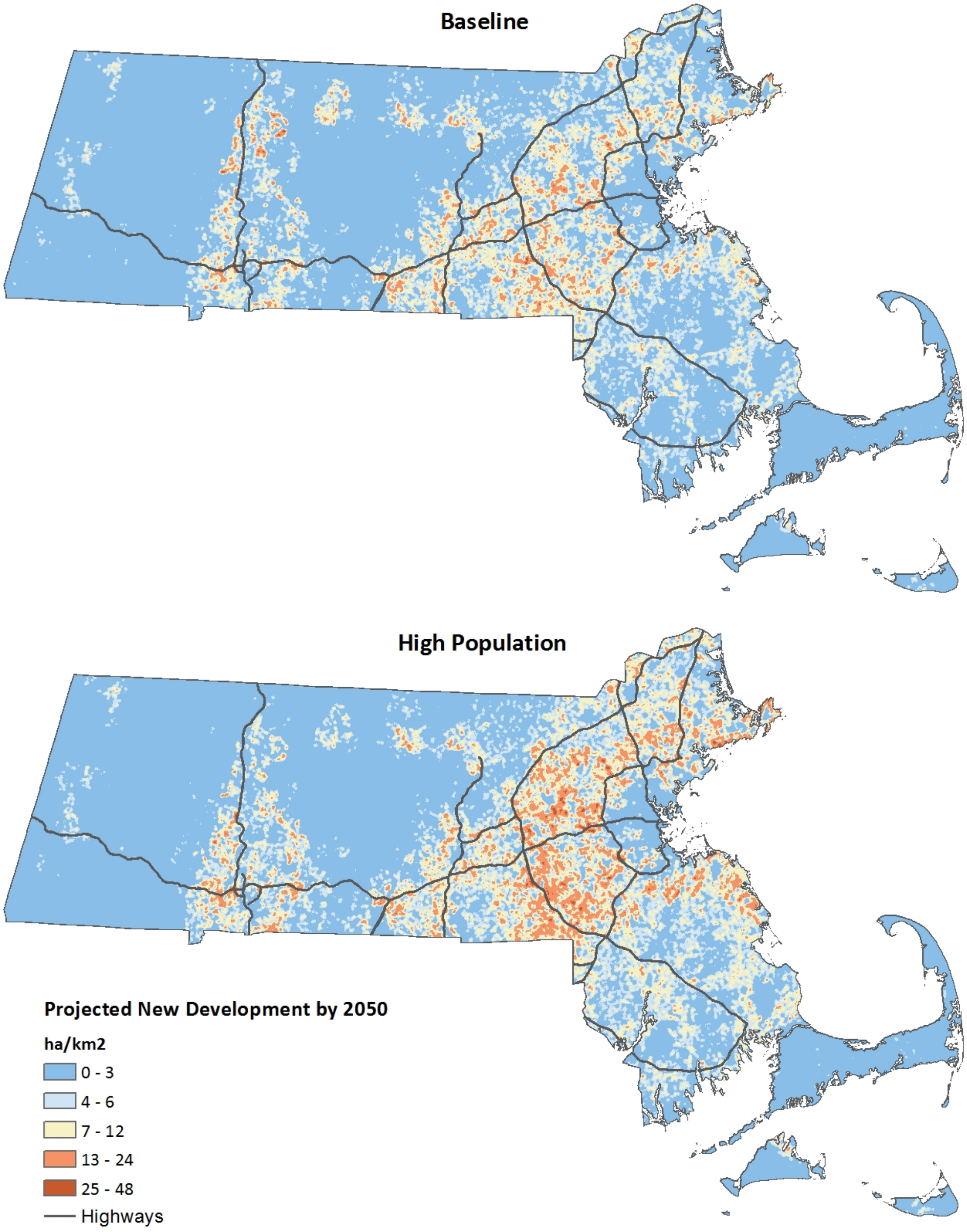


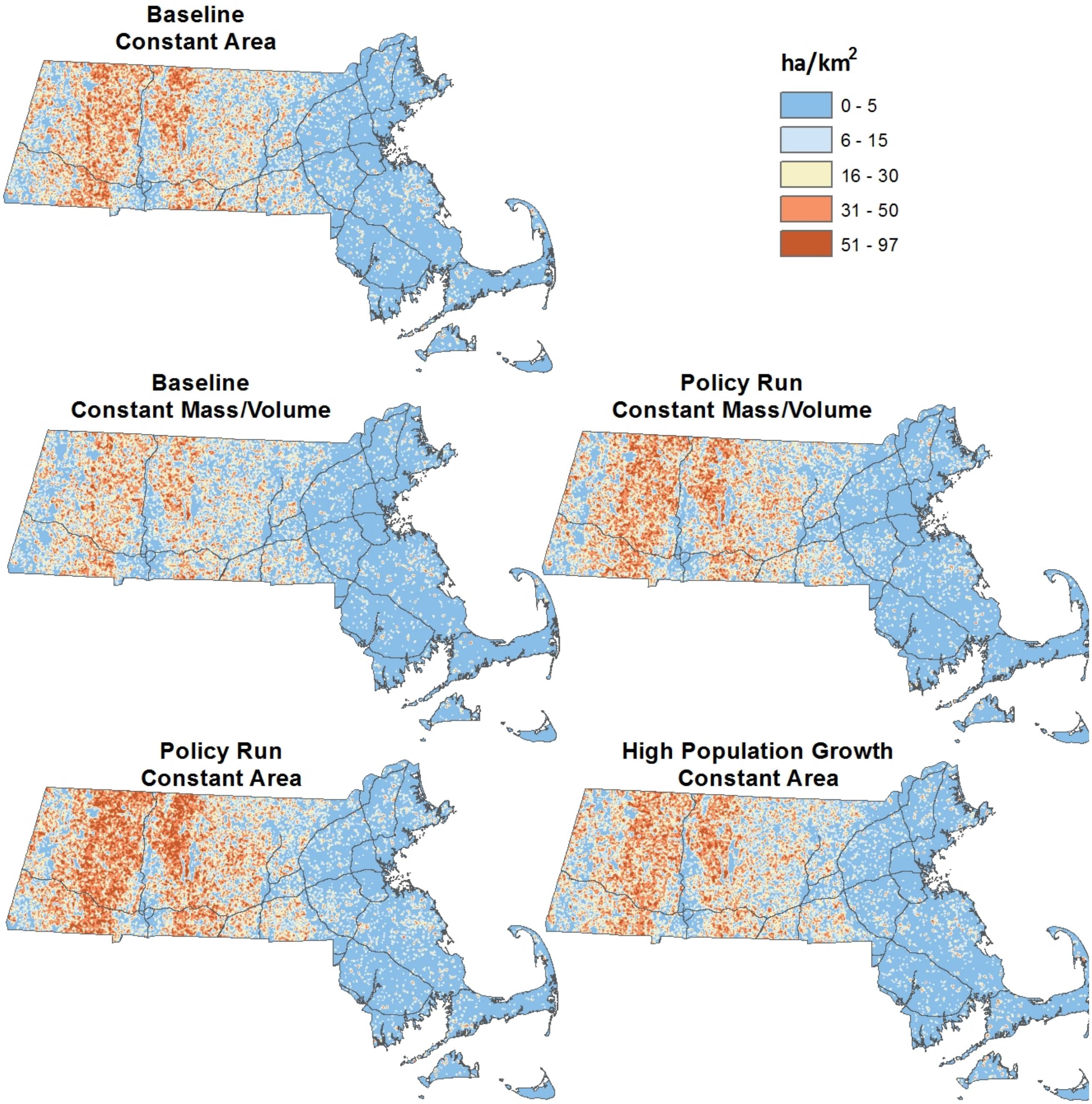
Figure 22: Spatial Allocation of new Built landcover. Baseline rates of conversion to new Built landcover are used the BL_A, BL_{MV}, PR_A, and PR_{MV} scenarios. High Population rates of conversion to new Built landcover are used in the HPG_A scenario. This map shows the density of simulated new Built patches using a 1km kernel density estimator to smooth and highlight the pattern of development.



Impact of Commercial Forestry on Live Carbon Stocks

Commercial timber harvesting occurred on 273,744 ha by 2050 in the BL_A scenario. The annual area harvested was kept constant throughout the simulation; therefore, the annual harvested volume/mass increased through time as the density of carbon increased due to forest growth (Figure 15). The annual live removed carbon due to forestry increased from 0.42 Tg yr^{-1} in year 2020 to 0.63 Tg yr^{-1} in year 2050 (1.5 to 2.3MMT of CO_2eq, respectively). Harvesting was concentrated in the western half of the Commonwealth (Figure 23). Of the 18.62 Tg C (68.3 MMT of CO_2eq) removed by commercial harvests, 17.8% was stored in wood products and 17.3% remained on the landscape, either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Commercial forestry increased the rate of carbon sequestration on harvested sites due to higher growth rates in younger and lower stocked stands and reduced probability of mortality due to competition and wind. Enhanced carbon sequestration on the harvested sites increased carbon stocks by 6.87 Tg (25.2 MMT of CO_2eq), reducing the impact of forestry by 37% by 2050. Overall, commercial forestry in the BL_A scenario reduced live C stocks by 11.75 Tg. After accounting for the fate of harvested carbon and enhanced sequestration, commercial forestry resulted in a net emission of 5.22 Tg C (19.2 MMT of CO_2eq), relative to a counterfactual scenario with no LULC change.

Figure 23. Spatial Allocation of Harvest for all simulations. This map shows the density of simulated harvest patches using a 1km kernel density estimator to smooth and highlight the pattern of harvest.



4.2.2 **Baseline with Constant Harvest Mass/Volume (BL_{MV})**

Aggregate changes in carbon

In the BL_{MV} scenario, forest growth increased total live carbon in Massachusetts to 171.0 Tg (+ 39.1%) by the year 2050 (Table 10). Between 2020 and 2050, development and commercial forestry removed 17.53 Tg of live carbon (64.3 MMT of CO_2eq; Figure 21). Of that removed carbon, 2.43 Tg C was stored in wood products and 2.42 Tg C remained on the landscape either in landfills or as logging slash that had not yet decomposed by

2050 (Table 10). Therefore, the total direct emissions associated with LULC change (i.e., commercial forestry, incidental harvesting, and development) in this scenario was 13.48 Tg C (49.5 MMT of CO_2eq). Afforestation increased live carbon by 0.07 Tg. In addition, LULC change impacted terrestrial carbon stores via its impacts on ecosystem dynamics. Specifically, an estimated 2.14 Tg C of sequestration was forgone by converting forests for development. Forestry enhanced rates of forest growth, which increased carbon stocks by 4.83 Tg. Accounting for all these factors, the net impact of LULC change in the BL_{MV} scenario was a 10.79 Tg reduction in carbon by the year 2050 (Table 10), compared to a counterfactual scenario with no LULC change.

Impacts of development on live carbon stocks

The BL_{MV} scenario envisioned the same rate and pattern of land-cover change as the BL_A scenario. Consequently, development in the BL_{MV} scenario had the nearly same impact level of carbon emissions, 5.26 Tg, with 59% coming directly from loss of forest carbon and 41% (Table 10) from forgone sequestration through 2050. The small variation between scenarios reflects stochastic processes and interaction with the commercial harvest regime (e.g., when a site is developed where a harvest previously occurred).

Impact of Commercial Forestry on Live Carbon Stocks

Commercial timber harvesting occurred on 216,453 ha by 2050 in the BL_{MV} scenario. The annual volume/mass of live harvested carbon was kept constant at approximately 0.41 Tg/yr (Figure 15). The annual harvested area required to meet the volume/mass target declined from 7661 ha/yr in 2020 to 5124 ha/yr in 2050 as forest carbon density increased due to forest growth. The spatial allocation of harvesting was similar to the BL_A scenario, but with lower harvest density statewide (Figure 23). Of the 14.41 Tg carbon removed by commercial harvest, 16.9% was stored in wood products and 16.8% remained on the landscape, either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Commercial forestry increased the rate of carbon sequestration on harvested sites due to higher growth rates in younger and lower stocked stands and reduced probability of mortality due to competition and wind. Enhanced carbon sequestration on the harvested sites increased carbon stocks by 4.83 Tg, reducing the impact of forestry by 33% by 2050. Overall, commercial forestry in the BL_{MV} scenario reduced live C stocks by 9.58 Tg. After accounting for the fate of harvested carbon and enhanced sequestration, commercial forestry resulted in a net emission of 4.73 Tg C (17.36 MMT of CO_2eq), relative to a counterfactual scenario with no LULC change.

4.2.3 **Policy Run with Constant harvest area (PR_A)**

Aggregate changes in live carbon stocks

In the PR_A scenario, forest growth increased total live carbon in Massachusetts to 167.4 Tg (+36.6%) by 2050 (Table 10). Between 2020 and 2050, development and commercial forestry removed 25.71 Tg of live carbon. Of that removed carbon, 3.98 Tg C was stored in wood products and 3.89 Tg C remained on the landscape either in landfills or as logging slash that had not yet decomposed by 2050 (Figure 21, Table 10). Therefore, the total direct emissions associated with LULC change (i.e., commercial forestry, incidental harvesting, and development) in this scenario was 18.62 Tg C. Afforestation increased live carbon by 0.07 Tg. In addition, LULC change impacted terrestrial carbon stores via its impacts on ecosystem dynamics. Specifically, an estimated 2.16 Tg of carbon sequestration was forgone by converting forests to development. Forestry enhanced rates of sequestration, which increased carbon stocks by 9.41 Tg. Accounting for all these factors, the net impact of LULC change in the PR_A scenario was a 11.37 Tg reduction in carbon by the year 2050 (Table 10) compared to a counterfactual scenario with no LULC change.

Impacts of development on live carbon stocks

The PR_A scenario envisioned the same rate and pattern of land-cover change as the BL_A scenario. Consequently, development in the PR_A scenario had the nearly same impact level of carbon emissions, 5.26 Tg, with 59% coming directly from loss of forest carbon and 41% (Table 10) from forgone sequestration through 2050. The small variation between scenarios reflects stochastic processes and interaction with the commercial harvest regime (e.g., when a site is developed where a harvest previously occurred).

Impact of Commercial Forestry on Live Carbon Stocks

In the PR_A scenario, commercial timber harvesting occurred on 341,249 ha by the year 2050. In this scenario, the area harvested was kept constant through time; therefore, the annual harvested volume/mass increased through time as the density of carbon increased due to forest growth. The annual harvested carbon increased during the simulation from 0.52 Tg in 2020 to 0.75 Tg in 2050 (Figure 15). The spatial allocation of harvests is similar to the two baseline scenarios, except that overall densities are higher, particularly in central Massachusetts (Figure 23). Of the 22.61 Tg C removed by commercial harvests, 17.6% was stored in wood products and 17.2% remained on the landscape, either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Commercial forestry increased the rate of carbon sequestration on harvested sites due to higher growth rates in younger and lower stocked stands and reduced probability of mortality due to competition and wind. Enhanced carbon sequestration on the harvested sites increased carbon stocks by 9.41 Tg reducing the impact of forestry by 42% by 2050. Overall, commercial forestry in the PR_A scenario reduced live C stocks by 13.2 Tg. After accounting for the fate of harvested carbon and enhanced sequestration, commercial forestry resulted in a net emission of 5.33 Tg C (19.56 MMT of CO_2eq), relative to a counterfactual scenario with no LULC change.

4.2.4 **Policy Run with Constant harvest Mass/Volume (PR_{MV})**

Aggregate changes in live carbon stocks

In the PR_{MV} scenario, forest growth increased total live carbon in Massachusetts to 169.9 Tg (+38.7%) by the year 2050 (Table 10). Between 2020 and 2050, development and commercial forestry removed 21.29 Tg of live carbon. Of that removed carbon, 3.06 Tg C was stored in wood products and 3.05 Tg C remained on the landscape either in landfills or as logging slash that had not yet decomposed by 2050 (Figure 21, Table 10). Therefore, the total direct emissions associated with LULC change (i.e., commercial forestry, incidental harvesting, and development) in this scenario was 15.97 Tg C. Afforestation increased live carbon by 0.07 Tg. In addition, LULC change impacted terrestrial carbon stores via its impacts on ecosystem dynamics. Specifically, an estimated 2.15 Tg of carbon sequestration was forgone by converting forests to development. Forestry enhanced rates of sequestration, which increased carbon stocks by 7.43 Accounting for all these factors, the net impact of LULC change in the PR_{MV} scenario was a 10.69 Tg reduction in carbon by the year 2050 (Table 10) compared to a counterfactual scenario with no LULC change.

Impacts of development on live carbon stocks

The PR_{MV} scenario envisioned the same rate and pattern of land-cover change as the BL_A scenario. Consequently, development in the PR_{MV} scenario had the nearly same impact level of carbon emissions, 5.26 Tg, with 59% coming from directly from loss of forest carbon and 41% (Table 10) from forgone sequestration through 2050. The small variation between scenarios reflects stochastic processes and interaction with the commercial harvest regime (e.g., when a site is developed where a harvest previously occurred).

Impact of Commercial Forestry on Live Carbon Stocks

In the PR_{MV} scenario, commercial timber harvesting occurred on 279,521 ha by the year 2050. In this scenario, the annual volume/mass of live harvested carbon was kept constant at approximately 0.51 Tg/yr throughout the simulation (Figure 16). As forest carbon density increased due to forest growth, the annual area harvested declined from 9,646 ha/yr in 2020 to 6,772 ha/yr in 2050. The spatial allocation of harvests was similar to the policy run with Constant area; however, harvest density was lower overall due to declining harvest areas over time (Figure 23). Of the 18.18 Tg C removed by commercial harvests, 16.8% was stored in wood products and 16.8% remained on the landscape, either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Commercial forestry increased the rate of carbon sequestration on harvested sites due to higher growth rates in younger and lower stocked stands and reduced probability of mortality due to competition and wind. Enhanced carbon sequestration on the harvested sites increased carbon stocks by 7.43 Tg reducing the impact of forestry by 41% by 2050. Overall, commercial forestry in the PR_{MV} scenario reduced live C stocks by 10.75 Tg. After accounting for the fate of harvested carbon and enhanced sequestration, commercial forestry resulted in a net emission of 4.64 Tg C (17.03 MMT of CO_2eq), relative to a counterfactual scenario with no LULC change.

4.2.5 **High Population Growth with Constant Harvest Area (HPGA)**

Aggregate changes in live carbon stocks

In the HPG_A scenario, forest growth increased total live carbon in Massachusetts to 167.75 Tg (+36.5%) by the year 2050 (Table 10). Between 2020 and 2050, development and commercial forestry removed 22.49 Tg of live carbon. Of that removed carbon, 3.29 Tg C was stored in wood products and 3.21 Tg C remained on the landscape either in landfills or as logging slash that had not yet decomposed by 2050 (Figure 21, Table 10). Therefore, the total direct emissions associated with LULC change (i.e., commercial forestry, incidental harvesting, and development) in this scenario was 16.77 Tg C. Afforestation increased live carbon by 0.07 Tg. In addition, LULC change impacted terrestrial carbon stores via its impacts on ecosystem dynamics. Specifically, an estimated 2.5 Tg of carbon sequestration was forgone by converting forests to development. Forestry enhanced rates of sequestration, which increased carbon stocks by 6.85 Tg. Accounting for all these factors, the net impact of LULC change in the HPG_A scenario was a 12.42 Tg reduction in carbon by the year 2050 (Table 10) compared to a counterfactual scenario with no LULC change.

Impacts of development on live carbon stocks

The HPG_A scenario included 62,499 ha of new built land cover and 57,776 ha of forest loss by 2050 (Table 3). The spatial allocation of this new development generally matched the pattern found in the BL_A scenario, albeit with greater sprawl into exurban areas and denser infill around the I-95 and I-495 highway corridors (Figure

22). The development pattern in the HPG_A scenario also had a higher proportion of new development in the eastern part of the Commonwealth. Forest loss reduced carbon stocks by 6.43 Tg C (Table 10), relative to a counterfactual scenario with no LULC change. Of that, 61% of the reduction was from direct emissions caused by the clearing of trees and 39% was due to forgone carbon sequestration through 2050.

Impact of Commercial Forestry on Live Carbon Stocks

In the HPG_A scenario, commercial timber harvesting occurred on 275,002 ha by the year 2050. In this scenario, the annual area harvested is held constant through time; therefore, the annual harvested volume/mass increased as the density of carbon increased due to forest growth. The annual live harvested carbon increased from 0.42 Tg yr^{-1} in 2020 to 0.63 Tg yr^{-1} in 2050. The spatial allocation of harvests in the HPG_A scenario run was identical to the BL_A scenario, except for some minor variations due to the stochastic processes within the harvest model (Figure 23). Of the 18.56 Tg C removed by commercial harvests, 17.7% was stored in wood products and 17.3% remained on the landscape, either in landfills or as logging slash that had not yet decomposed by 2050 (Table 10). Commercial forestry increased the rate of carbon sequestration on harvested sites due to higher growth rates in younger and lower stocked stands and reduced probability of mortality due to competition and wind. Enhanced carbon sequestration on the harvested sites increased carbon stocks by 6.85 Tg, reducing the impact of forestry by 37% by 2050. Overall, commercial forestry in the HPG_A scenario reduced live C stocks by 11.71 Tg. After accounting for the fate of harvested carbon and enhanced sequestration, commercial forestry resulted in a net emission of 5.21 Tg C (19.12 MMT of CO_2eq), relative to a counterfactual scenario with no LULC change.

4.3 Impacts of LULC change on Soil Organic Carbon

Changes to SOC stocks in the scenarios were commensurate with changes in land cover (Table 11). The Baseline and Policy scenarios (BL_A, BL_{MV}, PR_A, and PR_{MV}) reduced SOC stocks by 10.9 Tg by the year 2050. These scenarios all have the same types and patterns of land-cover change and, therefore, the same estimated change in SOC. The HPG_A scenario had greater rate of development and associated loss of forest, which resulted in the loss of 13.9 Tg of SOC. In the modeling framework, commercial forestry does not cause a change in land-cover and, therefore, does not affect estimates of soil carbon.

Table 11. Changes to soil organic carbon based on carbon density estimates from the Healthy Soils Action Team. The Baseline and Policy scenarios (BLA, BLMV, PRA, and PRMV) all have the same level of land-cover change and, therefore, the same estimated change in SOC.

CCDC Land-cover	Total SOC (Tg) 2020	Baseline & Policy		High Population	
		Total SOC (Tg) 2050	Change	Total SOC (Tg) 2050	Change
Built	42.5	46.9	4.4	48.4	5.9
Forest	373.7	362.8	-10.9	359.2	-14.4
Pasture & Agriculture	15.6	15.9	0.2	15.6	0.0
Water	0.0	0.0	0.0	0.0	0.0
Other	43.7	39.2	-4.6	38.4	-5.3
Total	**475.6**	**464.7**	**-10.9**	**461.7**	**-13.9**

4.4 Impacts of Other LULC Changes

All the scenarios described above included several other LULC processes. The rate and intensity of these processes was constant among all scenarios. Based on patterns observed in the CCDC data, afforestation occurred on 6,017 ha by 2050, largely in southeastern Massachusetts on fallowed cranberry bogs. Permanent conversion of forest to Pasture & Agriculture occurred on 8,221 ha by 2050, which emitted 0.85 Tg of carbon from all pools by 2050. Finally, incidental harvests removed 6% of forest biomass over approximately 150,000 ha by 2050. Total removals were approximately 0.80 Tg. No attempt was made to quantify any impacts of incidental harvesting on subsequent rates of forest growth.

5 Discussion

In all the LULC change scenarios, forest growth exceeds removals and Massachusetts continues to be a net carbon sink, with between 36% and 39% more live carbon in the forests by 2050 (Figure 20). Nonetheless, LULC change had significant impacts on terrestrial carbon stocks. The LULC changes depicted in the scenarios reduced carbon stores in 2050 by 9.9 to 11.6 Tg C, relative to a counterfactual scenario with no LULC change.

There are only small differences among the simulated scenarios in terms of their impact on statewide carbon stores in 2050. Rather than LULC change, the primary mechanism controlling terrestrial forest carbon dynamics (excluding soil organic carbon) is continued forest growth, which has a strong element of landscape inertia that's been building since the mid nineteenth century. Forest growth was also enhanced by simulated climate change and elevated CO_2 concentrations, particularly later in the simulations. While several studies have documented a growth enhancement attributable to climate change and greater CO_2,[123] [124] there remains significant uncertainty as to whether the effect will be sustained in the future. For this reason, the rates of growth reported in these simulations should be seen as an upper bound on potential forest carbon sequestration.

This study explicitly accounts for the impacts of LULC change on subsequent ecosystem processes and associated carbon dynamics. This approach permits a more complete accounting of the impacts of LULC change during the study period. In the scenarios, conversion of forests to Built cover (i.e., development) removed most live carbon (i.e., 70%) and stops all future sequestration on the site. Forgone sequestration accounts for approximately 40% of the total carbon impact by 2050. The impacts of forgone sequestration accrue over time; therefore, magnitude is affected by the timing of conversion within the simulations. Because the scenarios had more development in the early time steps, this effect was bigger than it would have been were the conversion spread evenly through time or if it were concentrated at the end of the scenarios.[125] Also, while not reported here, the impacts of forgone sequestration due to forest loss will continue to compound beyond 2050. The analysis included the simplifying assumption that no carbon sequestration occurs on Built land cover, even though when a forest is converted to Built approximately 30% of the forest carbon is retained to represent yard and street trees. This assumption was used because tree growth in these conditions is not well-described by science. Urban and suburban trees tend to grow faster but also die younger than trees in the forest interior.[126] And while growth along temperate forest edges can be faster than in the interior,[127] the effect is variable between urban and rural settings[128] and cannot be estimated with the LANDIS/PnET modeling

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[123] Walker et al., *Integrating the Evidence for a Terrestrial Carbon Sink Caused by Increasing Atmospheric CO 2 , New Phytologist*, 2020.

[124] Keenan et al., "Net Carbon Uptake Has Increased through Warming-Induced Changes in Temperate Forest Phenology," *Nature Climate Change* 4, no. 7 (2014): 598–604.

[125] The decline in the rate of development in the later timesteps was associated with a decline in the population growth within the DOT projections. No similar decline was included in the timber harvest scenario, which maintained either constant harvest area or constant harvested mass/volume, depending on scenario.

[126] Smith, Dearborn, and Hutyra, "Live Fast, Die Young: Accelerated Growth, Mortality, and Turnover in Street Trees," *PLoS ONE* 14, no. 5 (2019): 1–17.

[127] Reinmann and Hutyra, "Edge Effects Enhance Carbon Uptake and Its Vulnerability to Climate Change in Temperate Broadleaf Forests."

[128] Reinmann, A. B., Smith, I. A., Thompson, J. R. & Hutyra, L. R. 2020 Urbanization and fragmentation mediate temperate forest carbon cycle response to climate. *Environ. Res. Lett.*

framework used here. Nonetheless, the assumption of zero sequestration on Built land cover, while the best available option for this study, likely inflated the estimated impact of development on carbon stocks.

From 1990 to 2017, CCDC data indicate a total conversion of 49,000 ha of land to the Built and Agricultural classes, or about 1,800 ha per year.[129] EEA's estimations of land demands based on UMDI's population and housing forecasts range from 46,000 to 62,500 ha of cumulative land conversions by 2050, depending on the projection scenario. Because the rate of land-cover change into the Built class was estimated by EEA staff based on the relationship between population change, building permits, and building footprints, it primarily accounts for land-cover change associated with the development of commercial and residential buildings, with fractional set-asides for accessory developments on the developed parcels, such as lawns and driveways, as well as some incremental public infrastructure requirements, such as public roads and power lines. This approach assumes new development requires only marginal new infrastructure. Similarly, the recent trends on which this analysis was based include some development of ground-mounted solar, implicitly building some of this conversion demand into the infrastructure adjustment. However, this estimate does not incorporate explicit estimates of total land needs for widespread deployment of clean energy infrastructure. This dynamic is discussed at greater length in the companion *Energy Pathways Report* and the *Roadmap Report*.

In contrast to development, timber harvesting affected subsequent ecosystem dynamics by increasing the rate of sequestration relative to what would have occurred without harvesting. This occurs because forest growth is enhanced by the additional light and other resources that harvesting makes available to the remaining trees. It also lowers the average tree cohort age, which increases growth; and it lowers the probability of tree mortality due to competition and wind. In the LULC scenarios, more rapid growth (i.e., enhanced sequestration) after harvesting reduced the impact of commercial forestry on carbon stocks. Figure 24 shows the loss of carbon stocks and the growth trajectory for stands harvested at different time steps. While harvested stands never "catch up" to the unharvested stands within the study period, in terms of total ecosystem carbon stocks, the rate of accumulation is faster. This pattern is consistent with other studies that demonstrate that the maximum live carbon stocking is achieved without harvesting.[130] [131]

Some assumptions built-in to the LANDIS/PnET model affect these estimates and are worth considering. Importantly, the model incorporates a conventional age-related growth decline. Because there are so few remaining older forests, the rate of age-related decline is not well-constrained by empirical studies. A recent synthesis of long-term measurements at the Harvard Forest suggests that forest growth rates are maintained and can even accelerate much later into forest development than was previously recognized.[132] That said, several long-term empirical studies have documented a stand-level growth enhancement after partial

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[129] Pasquarella and Holden, "Annual Land Cover Products for Massachusetts." DOI: 10.5281/ZENODO.3531893

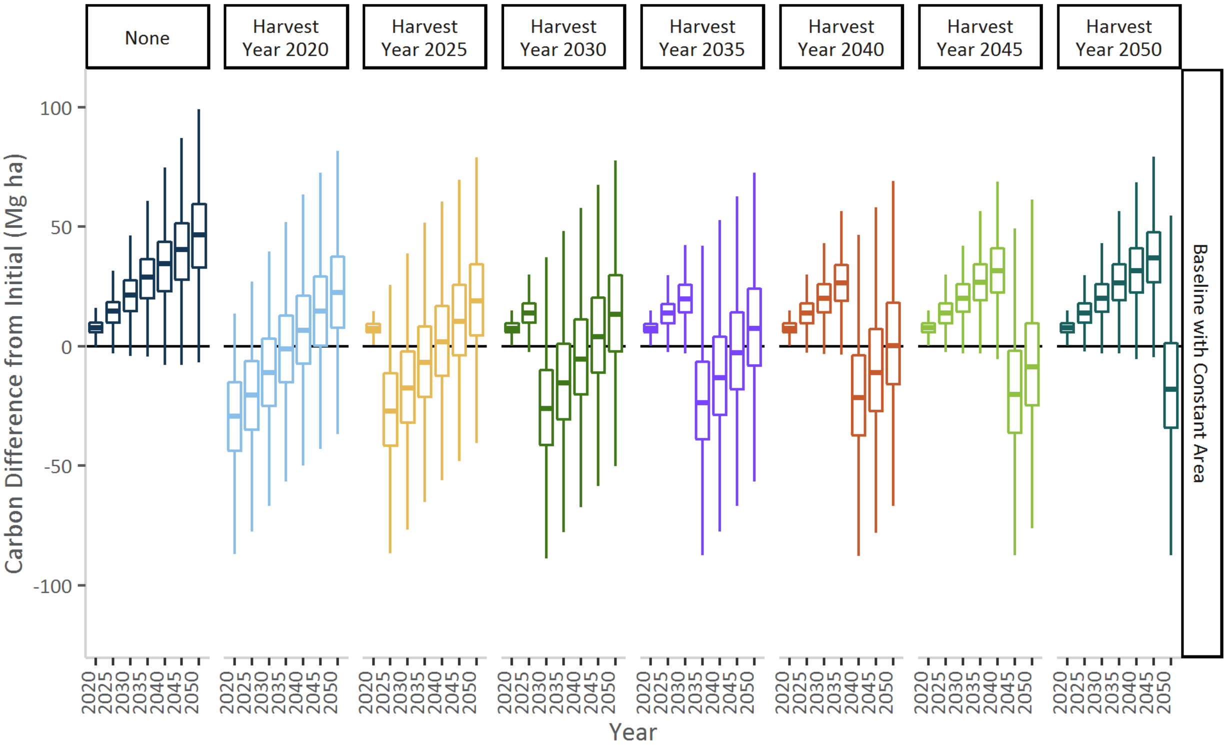
[130] Nunery and Keeton, "Forest Carbon Storage in the Northeastern United States: Net Effects of Harvesting Frequency, Post-Harvest Retention, and Wood Products."

[131] Puhlick et al., "Long-Term Influence of Alternative Forest Management Treatments on Total Ecosystem and Wood Product Carbon Storage," *Canadian Journal of Forest Research* 46, no. 11 (2016): 1404–12.

[132] Finzi et al., "The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change."

harvesting or disturbance.[133] [134] [135] [136] The growth enhancement simulated in LANDIS/PnET is somewhat larger and more sudden than what was reported in these studies, therefore the estimates of enhanced sequestration due to harvesting should be seen as near the upper limit of what might be achieved.

Figure 24. Growth trajectories for harvested and unharvested stands in the baseline scenario. Growth trajectory and final C density for cells harvested at differing timesteps or never harvested. Values indicate difference from the initial cell C density. Harvested cells were filtered to only include cells that had a single harvest. Outliers are not shown in this figure.



The analysis of LULC change on soil organic carbon suggests that losses from the soil due to forest conversion to Built cover could be of an equal or greater magnitude than losses from live carbon from all LULC change combined. This finding is significant but has some caveats. Despite its importance, below-ground carbon has been far less studied than aboveground carbon. The data used in this study were derived from the Massachusetts Healthy Soils Action plan research team. This group re-analyzed data collected by the NRCS and established estimates of forest SOC density that are much higher than most previously published estimates. The estimated 279 Mg/ha of forests SOC used here was based on a spatially weighted average of the Healthy Soils' forest and forested wetland land-cover classes; this is much higher than most other forest estimates

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[133] Carter et al., "Effects of Multiaged Silvicultural Systems on Reserve Tree Growth 19 Years after Establishment across Multiple Species in the Acadian Forest in Maine, USA," *Canadian Journal of Forest Research* 47, no. 10 (2017): 1314–24.

[134] Plotkin et al., "Survivors , Not Invaders , Control Forest Development Following Simulated Hurricane Author (s): Audrey Barker Plotkin , David Foster , Joel Carlson and Alison Magill Published by : Wiley on Behalf of the Ecological Society of America Stable URL : Https:" 94, no. 2 (2013): 414–23.

[135] Davis et al., "Forest Carbon Sequestration Changes in Response to Timber Harvest," *Forest Ecology and Management* 258, no. 9 (2009): 2101–9.

[136] D'Amato et al., "Forest Management for Mitigation and Adaptation to Climate Change: Insights from Long-Term Silviculture Experiments," *Forest Ecology and Management* 262, no. 5 (2011): 803–16.

from the region. For example, average soil carbon at the Harvard Forest in central Massachusetts is 125 to 150 Mg ha.[137] At the Hubbard Brook experimental forest in NH, SOC is estimated at 158 Mg ha.[138] Their estimate for SOC in Built land cover was 94 Mg ha, which is slightly lower than other studies done in the region. Raciti et al., working in and around Boston, estimated residential SOC at ~ 125 Mg ha.[139] Contosta et al. estimated residential carbon in Manchester NH at 108 Mg ha.[140] The 185 Mg ha difference between the Healthy Soils' Forest and Built Classes meant that when a hectare was converted the carbon loss below ground was often 3 to 5 times greater than the loss above ground. This is much larger than most other studies suggest. For example, Raciti et al. found no difference in SOC between yards and adjacent forests, though, differences in methodologies prevent a clear comparison.

One additional consideration relates to the impacts of forestry on soil carbon. In this analysis, change in soil carbon was linked to change in land-cover class; since forestry does not cause a change in the cover class, it had no impact on soil carbon. However, forestry does impact soil carbon, but those impacts vary widely based on forestry practices, including silvicultural practices and the time of year that harvests occur.[141] A metanalysis of harvest impacts on soil carbon in temperate forests worldwide found that, on average, harvesting reduced carbon stocks by 8%, though the impacts can be ephemeral.[142] Simply multiplying this average impact by the area harvested in the scenarios suggests that the inclusion of commercial forestry into the impact could increase carbon emissions by 2050 by an additional 4.8 to 7.6 Tg C, though this estimate is far from certain. For all these reasons, the findings regarding losses in soil carbon due to LULC should be interpreted with caution. Caveats notwithstanding, it is well established that soil carbon pools are large, slow to form, and can be emitted through land-use disturbance; therefore, conservation of soil carbon should remain an important consideration in land-use planning.

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[137] Finzi et al., "The Harvard Forest Carbon Budget: Patterns, Processes and Responses to Global Change."
[138] Fahey et al., "The Biogeochemistry of Carbon at Hubbard Brook," *Biogeochemistry* 75, no. 1 (2005): 109–76.
[139] Raciti et al., "Inconsistent Definitions of 'Urban' Result in Different Conclusions about the Size of Urban Carbon and Nitrogen Stocks," *Ecological Applications* 22, no. 3 (2012): 1015–35.
[140] Contosta et al., "Biogeochemical and Socioeconomic Drivers of Above- and below-Ground Carbon Stocks in Urban Residential Yards of a Small City," *Landscape and Urban Planning* 196, no. November 2019 (2020): 103724.
[141] Yanai et al., "Challenges of Measuring Forest Floor Organic Matter Dynamics: Repeated Measures from a Chronosequence," *Forest Ecology and Management* 138, no. 1–3 (2000): 273–83.
[142] Nave et al., "Harvest Impacts on Soil Carbon Storage in Temperate Forests."

6 Future Research and Opportunities

This technical report provides data and information designed to help the Commonwealth make decisions regarding LULC change and terrestrial carbon. It does not provide any policy analysis. The development of these models and outputs should facilitate future policy analysis and research. Here, the report concludes with some recommendations from the authors regarding potential next steps for this line of inquiry.

- *Consider additional LULC change scenarios:* The Commonwealth chose to consider LULC scenarios that contain relatively modest changes to the existing land-use regime. However, scenario research shows that alternative futures often need to be widely divergent to expand our thinking about what is possible.[143] Now that a modeling framework is in place, and the points of leverage are better understood, the Commonwealth can explore scenarios that are more divergent from current and historical trends. For example, to lessen the impact of LULC change on carbon emissions, scenarios might consider: more opportunities to increase afforestation, further decreasing building footprints, an increase in cluster development patterns, additional changes in forestry and wood utilization practices, or increasing rates of land protection. In contrast, to better understand the potential for future LULC change to increase carbon emissions, scenarios might consider: much greater rates of forest conversion associated with climate change-related migration, urban flight associated with the COVID-19 pandemic, large-scale buildout of energy infrastructure, or changes to wood or biomass markets that greatly increase the rate and/or intensity of harvesting.

- *Explore renewable energy build-out scenarios:* All of the proposed pathways to decarbonizing the economy include a substantial "at scale" build out of new solar and wind energy generation and supporting transmission infrastructure. Framed by the needs described in the energy system analysis in the *Energy Pathways Report*, the modeling framework developed here would allow the Commonwealth to explore and better understand the opportunities and tradeoffs associated with the construction of renewable energy infrastructure. Considerations like topographic aspect, proximity to electric transmission lines, environmental restrictions, local regulations, and ecological impacts could be added to the analysis. Due to inherent differences in current regional development pressures (e.g., eastern versus western MA), the local siting requirements, and disturbance intensity, the estimates of carbon costs associated with LULC change in this report are not appropriate for estimating the carbon costs of energy development.

- *Improve the harvested carbon analyses:* This study adapted a conventional approach to estimate the fate of harvested carbon in different pools. While this approach is widely used in research and policy applications, it includes several simplifications that could be improved. Using alternative approaches to assess the fate of harvested carbon that include the potential for greater wood utilization may have consequential impacts on these findings and would allow deeper consideration of the importance of new markets and improved technologies in the forestry sector.

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[143] McBride et al., "Increasing the Effectiveness of Participatory Scenario Development through Codesign," *Ecology and Society* 22, no. 3 (2017): art16.

- *Consider the co-benefits of forests:* This report focused exclusively on impacts of climate and LULC change on terrestrial carbon, which is just one dimension of the many values forests provide. There is now an opportunity to use these analyses to look for synergies between protecting forest carbon stocks while bolstering the resilience, ability to provision other services, including: clean water and wood products, flood mitigation, recreation opportunities, and other cultural services. Because the modeling framework explicitly incorporates the differential response of tree species to global change drivers, it is also uniquely suited to estimating effects on biodiversity and wildlife habitat.

7 Appendix

Table A1 Species-level parameter values used in the LANDIS/PnET forest landscape model. See User Guide[144] for details.

Common Name	Genus	Species	Species Code	Longevity	Sex Maturity	Shade Tolerance	Fire Tolerance	Seed Dispersal Effective	Seed Dispersal Maximum	Vegetative Reproduction Probability	Sprout Age Minimum	Sprout Age Maximum	Post Fire Regeneration
balsam fir	*Abies*	*balsamea*	abiebals	200	25	5	1	30	160	0	0	0	none
red maple	*Acer*	*rubrum*	acerrubr	235	5	4	1	100	200	0.75	0	150	none
sugar maple	*Acer*	*saccharum*	acersacc	300	40	5	1	100	200	0.1	0	60	none
yellow birch	*Betula*	*allegeniensis*	betualle	300	40	3	2	100	400	0.1	0	180	none
black birch	*Betula*	*lenta*	betulent	250	40	4	2	100	400	0.1	0	0	none
paper birch	*Betula*	*papyrifera*	betupapy	150	40	4	2	100	600	0.75	0	150	none
gray birch	*Betula*	*populifolia*	betupopu	150	40	4	2	100	400	0.1	0	0	none
pignut hickory	*Carya*	*glabra*	caryglab	200	30	3	2	50	100	0.25	0	200	resprout
American beech	*Fagus*	*grandifolia*	fagugran	300	10	5	1	30	300	0.7	10	200	resprout
white ash	*Fraxinus*	*americana*	fraxamer	300	30	2	1	70	140	0.1	0	70	none
black ash	*Fraxinus*	*nigra*	fraxnigr	150	30	4	2	200	2000	0.8	10	140	resprout
tamarack	*Larix*	*laricini*	larilari	180	35	2	2	100	400	0.2	0	0	none
hophornbeam	*Ostrya*	*virginiana*	ostrvirg	110	25	4	2	100	200	0.15	0	100	resprout
white spruce	*Picea*	*glauca*	piceglau	300	25	3	2	30	200	0	0	0	none
black spruce	*Picea*	*mariara*	picemari	215	30	3	3	79	158	0	0	0	none
red spruce	*Picea*	*rubens*	picerube	350	15	5	2	80	125	0	0	0	none
red pine	*Pinus*	*resinosa*	pinuresi	250	15	2	4	100	275	0.1	0	20	none
pitch pine	*Pinus*	*rigida*	pinurigi	200	10	2	4	90	150	0.5	10	100	resprout
white pine	*Pinus*	*strobus*	pinustro	400	25	3	3	60	210	0	0	0	none
loblolly pine	*Pinus*	*taeda*	pinutaed	350	15	2	4	45	200	0	0	3	none
balsam poplar	*Populous*	*balsamifera*	popubals	150	10	1	2	100	200	0.8	10	80	resprout
big tooth aspen	*Populous*	*grandidentata*	popugran	110	20	1	1	1000	5000	0.9	0	100	resprout
quaking aspen	*Populous*	*tremuloides*	poputrem	110	20	1	1	1000	5000	0.9	0	100	resprout
cherry	*Prunus*	*serotina*	prunsero	200	10	2	3	100	200	0.5	20	90	resprout
white oak	*Quercus*	*alba*	queralba	400	25	3	2	30	800	0.1	20	200	resprout
scarlet oak	*Quercus*	*coccinea*	quercocc	150	20	2	3	50	100	0.5	20	100	resprout
chestnut oak	*Quercus*	*prinus*	querprin	300	20	3	3	50	150	0.5	10	200	resprout
red oak	*Quercus*	*rubra*	querrubr	250	30	3	2	30	800	0.5	20	200	resprout
black oak	*Quercus*	*velutina*	quervelu	120	20	3	2	70	150	0.1	20	90	resprout
northern white cedar	*Thuja*	*occidentalis*	thujocci	800	30	2	1	45	100	0.5	0	200	none
basswood	*Tilia*	*americana*	tiliamer	250	15	4	1	75	150	0.8	10	240	resprout
American hemlock	*Tsuga*	*canadensis*	tsugcana	500	20	5	2	30	100	0	0	0	none
American elm	*Ulmus*	*americana*	ulmuamer	85	20	4	2	90	400	0.3	5	70	resprout

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[144] Gustafson and Miranda, "PnET-Succession v3.4 Extension User Guide," 2019.

Table A2. Species-level parameter values used in the LANDIS/PnET forest landscape model. See A1 for species names and User Guide[145] *for column definitions.*

PnET Species Code	KWd Lit	Fol Lignin	H3	H4	Fol N	SLW max	SLW Del	TO fol	Amax A	Amax B	Half Sat	Psn T Min	Psn TOpt	Psn T Max	k	Frac Below G	Frac Fol	FrActWd
abiebals	0.125	0.25	105	145	0.5	200	0	0.25	5.3	21.5	100	2	19	36	0.5	0.3	0.08	0.00002
acerrubr	0.081	0.11	111	152	1.5	80	0.2	1	-46	71.9	137	4	26	48	0.58	0.3	0.03	0.00004
acersacc	0.075	0.11	105	145	1.5	70	0.2	1	-46	71.9	100	2	23	44	0.58	0.4	0.03	0.00004
betualle	0.075	0.11	105	145	1.65	80	0.2	1	-46	71.9	175	3	21	39	0.58	0.4	0.03	0.00004
betulent	0.149	0.15	105	145	2.05	80	0.2	1	-46	71.9	137	3	21	39	0.58	0.4	0.03	0.00004
betupapy	0.075	0.11	105	145	1.4	80	0.2	1	-46	71.9	137	3	21	39	0.58	0.3	0.03	0.00004
betupopu	0.075	0.11	105	145	1.4	80	0.2	1	-46	71.9	137	3	21	39	0.58	0.4	0.03	0.00004
caryglab	0.166	0.17	111	152	1.56	90	0.2	1	-46	71.9	175	2	23	44	0.58	0.4	0.03	0.00004
fagugran	0.075	0.24	111	152	1.49	80	0.2	1	-46	71.9	100	2	23	44	0.58	0.4	0.03	0.00004
fraxamer	0.075	0.12	111	152	1.62	85	0.2	1	-46	71.9	175	3	25	47	0.58	0.4	0.03	0.00004
fraxnigr	0.075	0.12	111	152	1.62	85	0.2	1	-46	71.9	137	3	23	43	0.58	0.4	0.03	0.00004
larilari	0.125	0.25	118	160	1.38	110	0	1	5.3	21.5	213	1	20	39	0.58	0.4	0.12	0.00004
ostrvirg	0.075	0.12	111	152	1.24	90	0.2	1	-46	71.9	137	3	23	43	0.58	0.4	0.03	0.00004
piceglau	0.125	0.25	118	160	0.88	225	0	0.25	5.3	21.5	175	2	20	38	0.5	0.3	0.08	0.00002
picemari	0.125	0.25	118	160	0.63	225	0	0.25	5.3	21.5	175	2	20	38	0.5	0.3	0.1	0.00002
picerube	0.125	0.25	118	160	0.68	225	0	0.25	5.3	21.5	200	2	20	38	0.5	0.3	0.08	0.00002
pinuresi	0.125	0.25	118	160	0.9	225	0	0.333	5.3	21.5	213	3	21	39	0.5	0.4	0.12	0.00005
pinurigi	0.063	0.25	118	160	0.9	225	0	0.333	5.3	21.5	213	3	21	39	0.5	0.4	0.12	0.00005
pinustro	0.125	0.25	118	160	0.96	225	0	0.5	5.3	21.5	175	3	21	39	0.5	0.4	0.12	0.00004
pinutaed	0.125	0.25	118	160	0.78	225	0	0.333	5.3	21.5	213	5	30	55	0.5	0.4	0.12	0.00005
popubals	0.107	0.16	100	140	1.44	115	0.2	1	-46	71.9	250	0	21	42	0.58	0.3	0.03	0.00004
popugran	0.107	0.16	100	140	1.5	115	0.2	1	-46	71.9	250	2	22	42	0.58	0.3	0.03	0.00004
poputrem	0.107	0.16	100	140	1.5	115	0.2	1	-46	71.9	250	2	22	42	0.58	0.3	0.03	0.00004
prunsero	0.125	0.25	111	152	1.68	90	0.2	1	-46	71.9	213	3	25	47	0.58	0.4	0.03	0.00004
queralba	0.063	0.18	118	160	1.85	100	0.2	1	-46	71.9	175	2	26	50	0.58	0.4	0.03	0.00004
quercocc	0.05	0.17	118	160	1.25	95	0.2	1	-46	71.9	213	2	26	50	0.58	0.4	0.03	0.00004
querprin	0.17	0.26	111	152	1.99	81	0.2	1	-46	71.9	175	2	26	50	0.58	0.4	0.03	0.00004
querrubr	0.075	0.17	111	152	1.9	85	0.2	1	-46	71.9	175	2	24	46	0.58	0.4	0.03	0.00004
quervelu	0.17	0.18	111	152	1.9	76.5	0.2	1	-46	71.9	175	2	24	46	0.58	0.4	0.03	0.00004
thujocci	0.125	0.25	105	145	0.83	221	0	0.5	5.3	21.5	213	3	20	37	0.5	0.4	0.117	0.00005
tiliamer	0.075	0.12	111	152	1.9	67.5	0.2	1	-46	71.9	137	3	23	43	0.58	0.4	0.03	0.00004
tsugcana	0.024	0.25	105	145	1	195	0	0.333	5.3	21.5	100	3	21	39	0.5	0.3	0.08	0.00005
ulmuamer	0.075	0.12	105	145	2.29	76.5	0.2	1	-46	71.9	137	3	23	43	0.58	0.4	0.03	0.00004

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[145] Gustafson and Miranda.

Table A3. Carbon Densities for non-forest and non-urban land cover classes provided by Academic Advisory Committee.

Land Cover	Mg/ha C	Notes	Reference	Location
Pasture	6.8	Mean of Pasture and Hayfield (6.4795 Mg/ha) used to for Pasture & Agriculture class	Data from Seeta Sistla (unpublished data; samples collected 2016)	Southern VT
Hayfield	6.2	Mean of Pasture and Hayfield (6.4795 Mg/ha) used to for Pasture & Agriculture class	Data from Seeta Sistla (unpublished data; samples collected 2016)	Southern VT
Salt wetland	2.9		Tang et al. unpublished.	Cape Code, MA
Cranberry bog	1.9	Assumed to be identical to non-forest wetland (1.9 Mg/ha)	NA	Minnesota peatland
Non forested wetland	1.9		Weishampel P, R Kolka, and JY King. 2009. Forest Ecology & Management. 257:747-754.	
Barren natural	0.0	Assumed to be zero	NA	NA
Bare	0.0	Assumed to be zero	NA	NA

Table A4. Harvest Rx specifications. Rx Type is the Harvest Prescription and Goal provides an overview of the purpose of the removal. See Table A5 for definitions.

Rx Type	Goal
THIN	• Simulates intermediate cuttings in even-aged silvicultural systems. ○ Removes trees that are sick, poorly-formed, or low-grade. ○ Reallocates growing space for desirable, healthy, or well-formed trees to improve growth rate and rate of provision of ecosystem services. • The focus is on the residual stand, not beginning a new cohort. • May be of a wide range of removal intensities. • As implemented in the model, the prescription removed a greater proportion of biomass in more mature trees of species that are typically and historically more low-value and low-grade, without focusing on younger and middle-aged cohorts.
OSR Low Intensity	• Simulates regeneration cuttings in even-aged (shelterwood) and uneven-aged (irregular shelterwood) silvicultural systems that have moderate removal intensities. ○ Removes enough older trees to create conditions that are favorable for the establishment of seedlings (regeneration) either uniformly or irregularly across a stand while retaining a variable amount of residual older trees. • The focus can be on beginning a new cohort, but may also be on retaining older trees in the residual stand as a seed source, to shelter the younger trees for a period of time, or to create a complex horizontal or vertical structure across a stand. • As implemented in the model, the prescription removed much of the biomass of younger trees in equal proportions across higher- and lower-value species, and removed a much greater proportion of biomass in older trees of species that are typically and historically more low-value and low-grade. Very young cohorts representing advance regeneration were not affected.
OSR High Intensity	• Simulates regeneration cuttings in even-aged silvicultural systems that have higher removal intensities. ○ Removes enough older trees to create conditions that are favorable for the establishment of seedlings (regeneration) more uniformly across a stand. • The focus is on beginning a new cohort; and trees are retained in the residual stand only to the extent they act as a seed source or act as widely scattered individual or groups of trees for the sake of diverse conditions. • As implemented in the model, the prescription removed all biomass in younger cohorts but not so young as to affect advance regeneration, and a removed a greater proportion of biomass in older trees of species that are typically and historically more low-value and low-grade.
Uneven	• Simulates periodic cuttings in more regular uneven-aged silvicultural systems. ○ Treatments range from single-tree selection to group selection with patches of removed trees ranging from one to many tree-lengths in effective diameter. Within a patch, nearly all trees are typically removed (except for occasional reserve or seed trees); and between patches, thinnings of various types and intensities may occur. • The focus is on creating a periodic flow of ecosystem services from the stand. • As implemented in the model, a greater proportion of biomass of older trees was removed than younger trees; removal intensities were equal within age classes across lower- and higher-valued species except for middle-aged cohorts, where a greater proportion of biomass of lower-valued species was removed.

High-grade	• Simulates practices that remove trees of the highest financial value. ○ Little regard is given either to the residual stand or future cohorts. • The focus is typically maximization of short-term financial gain of the landowner, often to the detriment of long-term returns and productivity. • As implemented in the model, only older trees are removed, and double the proportion of biomass is removed of higher-value species than lower-value species. Very young cohorts representing advance regeneration were not affected.
THIN (EXR) & OSR Low Intensity (EXR)	• Simulates silvicultural systems that retain greater carbon stocks in the live tree carbon pool for a longer period of time, by extending the rotation length. • The focus is to realize a greater amount of carbon stored in live trees relative to business-as-usual rotation lengths. • The proportion of biomass removed in different species value groups was the same as the standard variants of these prescriptions.

Table A5. Harvest Prescription Glossary.

EXR – extended rotation period – extending harvest beyond usual economic maturity.

OSR – overstory removal – removal of dominant canopy trees.

Rotation period – time length between establishment of a stand of trees and when the stand is ready for a final cut (either when economically mature or reaching beyond natural maturity).

Shelterwood cut – silvicultural system in which trees are removed in a series of cuts designed to achieve a new even-aged stand under the shelter of remaining trees.