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# Opportunities for forest sector emissions reductions: a state-level analysis

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*Abstract.* The forest sector can play a significant role in climate change mitigation. We evaluated forest sector carbon trends and potential mitigation scenarios in Vermont using a systems-based modeling framework that accounts for net emissions from all forest sector components. These components comprise (1) the forest ecosystem, including land-use change, (2) harvested wood products (HWP), and (3) substitution effects associated with using renewable wood-based products and fuels in place of more emission-intensive materials and fossil fuel-based energy. We assessed baseline carbon trends from 1995 through 2050 using a business as usual (BAU) scenario. Emission reductions associated with different forest management and HWP scenarios were evaluated relative to the BAU scenario from 2020 to 2050. We estimated uncertainty for each forest sector component and used a Monte Carlo approach to estimate the distribution of cumulative total mitigation for each scenario relative to baseline. Our analysis indicates that the strength of the forest sector carbon sink in Vermont has been declining and will continue to decline over coming decades under the BAU scenario. However, several scenarios evaluated here could be effective in reducing emissions and enhancing carbon uptake. Shifting HWP to longer-lived commodities resulted in a 14% reduction in net cumulative emissions by 2050, the largest reduction of all scenarios. A scenario that combined extending harvest rotations, utilizing additional harvest residues for bioenergy, and increasing forest productivity resulted in a 12% reduction in net cumulative emissions. Shifting commodities from pulp and paper to bioenergy showed a 7.3% reduction in emissions. In contrast, shortening rotations to increase harvests for bioenergy use resulted in a 5.5% increase in emissions. In summary, model simulations suggest that net emissions could be reduced by up to 14% relative to BAU, depending on the management and HWP-use scenario. Combining multiple scenarios could further enhance reductions. However, realizing the full climate mitigation potential of these forests may be challenging due to socioeconomic barriers to implementation, as well as alternative management objectives that must be considered along with carbon sequestration.

*Key words: carbon emissions; climate change mitigation; forest carbon; harvested wood products; United States Climate Alliance; Vermont forests.*

## Introduction

Avoiding the most harmful effects of climate change will entail limiting the increase in global average temperatures to under 2°C above preindustrial levels (IPCC 2018). Achieving this ambitious objective will require attaining net negative emissions, globally, in the second half of this century (van Vuuren et al. 2011). In 2015, the United Nations adopted the Paris Agreement to achieve this goal by both reducing anthropogenic greenhouse gas (GHG) emissions and enhancing the removal of carbon dioxide ($CO_2$) from the atmosphere by natural sinks (UNFCCC 2015). The United States, the second largest emitter of GHGs in the world, committed to a net reduction of economy-wide GHG emissions of 26–28% by 2025 relative to 2005 levels (UNFCCC 2015). Although the U.S. federal government withdrew from the Paris Agreement from 2016 through 2020, a coalition of states (the U.S. Climate Alliance, USCA) has committed to uphold the objectives of the Agreement. The USCA has continued to grow and currently consists of 25 states, including much of the northeast, Great Lakes states, and Pacific coast.

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Forests can impact the global carbon cycle by sequestering carbon from the atmosphere and storing it in forest ecosystems and wood products, by producing biofuels that can substitute for fossil fuels, and by producing building materials that can substitute for more emissions-intensive materials. The U.S. forest sector currently offsets approximately 11% of gross annual GHG emissions from fossil fuel burning in the U.S. (US EPA 2019). A recent report by the Intergovernmental Panel on Climate Change (IPCC) concluded that limiting warming to less than 2°C will require mitigation measures that target forests and forest products (IPCC 2019). Increasing carbon sequestration through forest management, reforestation or afforestation, avoided deforestation, or expanded use of wood products and bioenergy have been recognized as important land-based mitigation options (IPCC 2019). Additional mitigation measures can be taken to reduce emissions related to disturbances (e.g., wildfires, insect outbreaks) and forest degradation (Canadell and Raupach 2008, Hurteau and North 2009, Nunery and Keeton 2010, D'Amato et al. 2011, Griscom et al. 2017, Fargione et al. 2018). However, the most effective and practical forest sector mitigation strategies are likely to vary regionally due to variation in climate, disturbance regimes and other drivers of ecosystem dynamics, and local and regional forest product markets (Smyth et al. 2020).

Vermont joined the USCA in 2017. Being the fourth most heavily forested state in the United States (by percent), Vermont has identified forests as playing a potentially important role in reducing the state's emissions. For instance, Vermont recognized maintaining and enhancing the role of forests in climate change mitigation in the state's 2017 Forest Action Plan (Vermont Department of Forests, Parks and Recreation 2017). Likewise, the state's Climate Action Commission has indicated the need for a baseline assessment of forest carbon stocks and sequestration and to identify actions that may support or promote additional sequestration by forests (Vermont Climate Action Commission 2018). Another state report on climate adaptation acknowledges the need for public and private programs to incentivize forest management practices that increase carbon sequestration (Vermont Department of Forests, Parks and Recreation 2015).

Evaluating forest mitigation potential requires a comprehensive systems perspective that accounts for net emissions from all components of the forest sector (Nabuurs et al. 2007), including (1) the forest ecosystem, accounting for land-use change, (2) harvested wood products (HWP), and (3) substitution effects associated with wood-based products and fuels (Appendix S1: Fig. S1).

Our study builds on past research that established a forest sector carbon modeling framework for evaluating forest management and HWP scenarios across sites in North America (Dugan et al. 2018, Olguin et al. 2018, Smyth et al. 2018). Here we apply this systems-based modeling methodology at a broader scale: the forest sector of the state of Vermont, USA. While previous studies looked at hypothetical scenarios, here we evaluated the effectiveness of forest management and HWP strategies outlined in the state's carbon management guidance (Vermont Department of Forests, Parks and Recreation 2015). In addition to informing Vermont managers and policy makers, our methodology and results may provide guidance for planners from other regions or USCA states that are considering forest-based mitigation strategies.

## Methods

### *Study area*

Vermont contains an estimated 1.8 million hectares of forest land, which account for approximately 76% of the state's land area (Morin et al. 2015). About 80% of the forestland is privately owned, with family forest owners collectively making up the largest ownership in the state (Morin et al. 2015). Green Mountain National Forest and other public ownerships (i.e., state, local, and municipal) each account for about 10% of the forestland (Appendix S1: Fig. S2). For this study, we present data and results for all forest ownerships combined.

Vermont's forests are dominated by hardwood stands. The Maple/Beech/Birch Forest Type Group (U.S. Forest Inventory and Analysis classification; USDA Forest Service 2018) covers about 71% of forestland (Fig. 1a). Forests in the eastern United States have had a long history of clearing for agriculture and unsustainable timber harvesting practices (Cogbill et al. 2002, Jeon et al. 2014), which resulted in a significant decline in carbon storage following European settlement (Birdsey et al. 2006). By the mid-20th century, a widespread forest reforestation effort and the adoption of more sustainable timber management allowed much of these degraded forestlands to regrow and carbon stocks to begin to recover.

This history of timber harvesting and forest restoration in the northeastern United States continue to play an important role in shaping forest structure, composition, and carbon dynamics today. In Vermont, the forest age structure shows a peak in stand establishment from the 1920s through 1960s, reflecting this period of forest restoration and regrowth (Fig. 1a). Currently, the forests of Vermont consist of mostly middle-aged to older stands, which tend to have higher carbon stocks but lower net volume increment than younger stands (Fig. 1 b). Furthermore, development pressures on private lands and around urban areas indicate that the trend of increasing forestland may be reversing (Wharton et al. 2003, Foster et al. 2010).

### *Data sets and modeling framework*

To assess the effects of forest management and harvested wood products (HWP) scenarios on forest sector

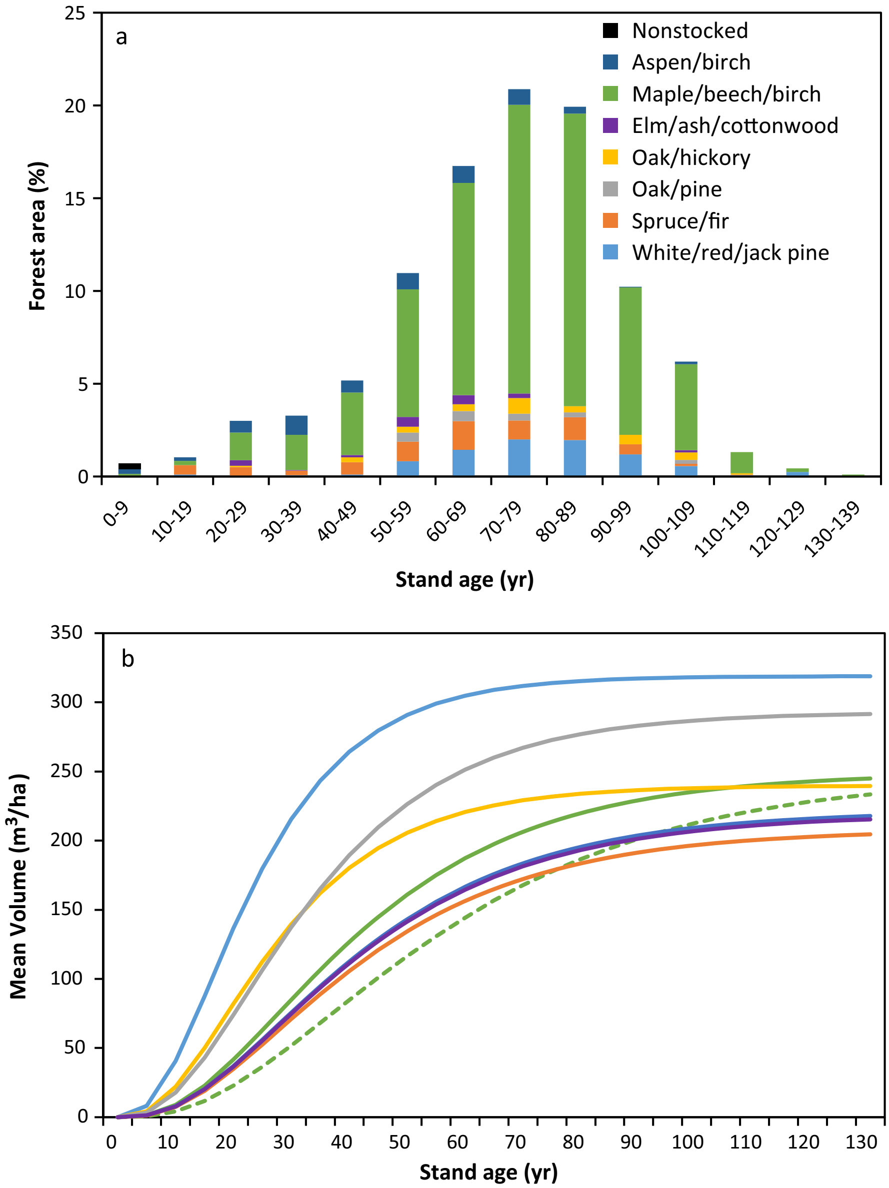


Fig. 1. (a) Stand age distribution in 2015 by forest type group for forests in Vermont, derived from Forest Inventory and Analysis data. (b) Regression-based mean volume curves for all forest type groups in Vermont. Maple/beech/birch curves are shown separately for private (solid green) and public (dashed green) land.

carbon stocks and emissions, we employed a carbon modeling framework that tracks carbon stocks and net emissions across the forest ecosystem and wood products sector, including substitution effects of wood products and wood-based energy. This framework has previously been applied at several study sites in the United States (Dugan et al. 2018). Here, we improve and extend the approach by using local timber harvest data collected by the state, updating parameters that describe wood-products substitution effects, including an uncertainty assessment, and simulating specific management scenarios outlined by managers and policymakers in Vermont (Vermont Department of Forests, Parks and Recreation 2015).

To evaluate forest ecosystem carbon flux, we used the spatially referenced growth-and-yield based Carbon Budget Model for the Canadian Forest Sector (CBM-CFS3; Kurz et al. 2009, Kull et al. 2011), parameterized with regional inventory data. The CBM-CFS3 uses a gain–loss carbon accounting approach (IPCC 2003), which derives initial carbon stocks from a starting forest inventory year, then estimates annual stock changes by summing the differences between gains (growth, afforestation/reforestation) and losses (mortality, harvesting, deforestation, decay). This method makes it possible to isolate the effects of individual factors (i.e., management, disturbances) on carbon dynamics, which is critical for scenario analyses.

To implement the CBM-CFS3, we used Forest Inventory and Analysis (FIA; USDA Forest Service 2018) data from the 2015 panel to estimate initial carbon stocks (data *available online*).[7] We stratified stands by ownership, FIA forest type group, stand age (Fig. 1a), and stand origin (naturally regenerated vs. planted), which allowed us to target management activities in our model scenarios to appropriate stand conditions. To model carbon accumulation, we used volume curves (Fig. 1b) derived from the Carbon Online Estimator (Van Deusen and Heath 2010). To estimate annual gains and losses of forest area from land use change (LUC; i.e., afforestation, reforestation, deforestation), we integrated remotely sensed information from the National Land Cover Database (NLCD; Homer et al. 2007, 2015, Fry et al. 2009). However, NLCD is a land cover product, not land use. Therefore, to reduce the likelihood of disturbances and harvests, and associated regeneration being classified as LUC, we constrained the NLCD product by classifying any changes between forest and grassland/herbaceous land cover as disturbances rather than permanent changes in land use. We estimated the annual area disturbed by insect, fire, and abiotic factors (wind, ice storm) using the North American Forest Dynamics data set (Goward et al. 2012) and ancillary data sets following Mascorro et al. (2016). To estimate the volume of timber harvested annually we used the Vermont Forest Resource Harvest reports, State Land Timber volume reports (Vermont Department of Forests, Parks and Recreation 2019), and U.S. Forest Service Cut and Sold Reports (USDA Forest Service 2019).

Carbon harvested from the forest ecosystem was tracked with the Carbon Budget Modelling Framework for Harvested Wood Products (CBMF-HWP) (Smyth et al. 2017). CBMF-HWP uses the IPCC production accounting approach (IPCC 2006, 2013) to estimate carbon emissions and storage from manufacturing of commodities, bioenergy, mill residues, domestic use and export, and post-consumer treatment of retired products (e.g., landfill, recycling, burning). We parameterized the CBMF-HWP with state and national-level statistics on timber production, timber product types (Fig. 2), utilization, post-consumer wood treatment, and product half-lives (Skog 2008, Dymond 2012, IPCC 2013, Howard and Jones 2016, USDA Forest Service 2018, Vermont Department of Forests, Parks and Recreation 2019). Given that none of our model scenarios focus on post-consumer treatment of wood, to simplify our analysis we assumed that all HWP carbon is emitted to the atmosphere when a product is retired. The ecosystem and HWP models include emissions from all GHGs, which were converted to carbon dioxide equivalents ($CO_2e$) using global warming potentials. To account for harvested wood carbon, we applied the Canadian approach in which all emissions and carbon storage from harvested wood are tracked exclusively in the HWP sector, thus we report emissions where and when they occur. In contrast, the IPCC approach applied by many European countries assumes that harvested wood carbon is emitted to the atmosphere (instantaneous oxidation) from the forest ecosystem and then taken up again as a sink in the HWP sector.

Last, to evaluate avoided emissions from substitution effects for each scenario, we used displacement factors (DF), which are defined as the metric tons of carbon emissions (Mg C) avoided per metric ton of wood carbon used (Sathre and O’Connor 2010). The end-use product mix influences the substitution effects of wood products with textiles and construction materials providing the largest benefits while substitution of furniture, packaging or chemicals may provide lower benefits (Leskinen et al. 2018). We used an average DF of 0.80 Mg C displaced per Mg C of saw and veneer logs produced, which assumes a mix of product categories including structural and non-structural construction materials, textiles, and other categories (furniture, packaging, chemicals) are displaced and no energy recovery at the end-of life stage (Leskinen et al. 2018). We used a bioenergy DF of 0.89 Mg C displaced per Mg C of bioenergy, estimated at the national level for Canada (Smyth et al. 2017), as there is no similar estimate available for the United States. This bioenergy DF assumes a mix of fossil fuel energy sources used for both heat and electricity production, including coal and petroleum coke, fuel oil, natural gas, and diesel are displaced, based on the energy fuel mixes across Canadian provinces (see Smyth et al. 2017: Table 6).

### *Scenario analysis*

We evaluated 11 potential mitigation scenarios that target the forest ecosystem and/or the product sector beginning in 2020 and running through 2050. Mitigation scenarios were selected from management options presented in *Creating and Maintaining Resilient Forests in Vermont: Adapting Forests to Climate Change* (Vermont Department of Forests, Parks and Recreation 2015) and personal communications with forest managers in the state. The scenarios are summarized in Table 1 and described in greater detail in Appendix S1: Section S3. The mitigation effect was calculated as

$$M = E_S - E_B$$

where $M$ is the mitigation effect, $E_S$ is the mitigation scenario emissions and $E_B$ is the baseline scenario emission, which assumes business as usual (BAU) management. Aside from the application of mitigation activities, each mitigation scenario is otherwise identical to the baseline scenario. Negative emissions indicate carbon

[7] https://www.fia.fs.fed.us/

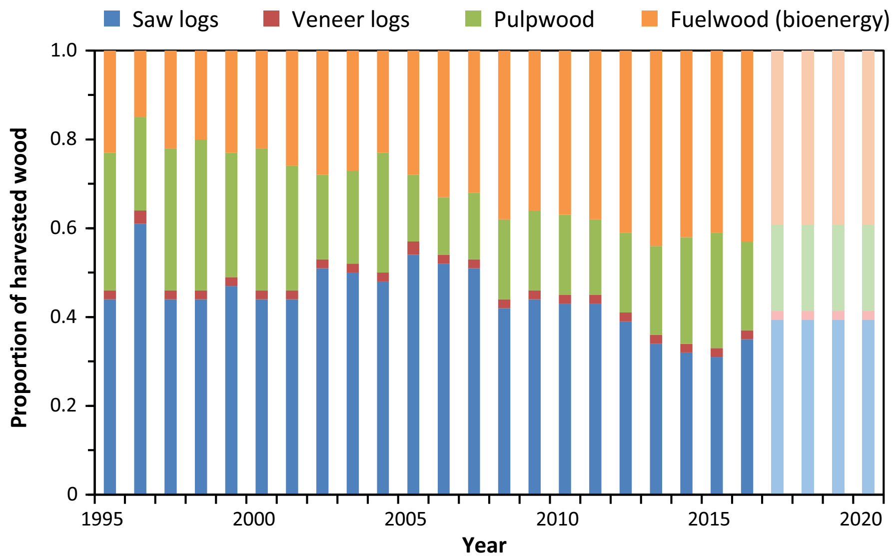


Fig. 2. Annualized proportions of roundwood removals in each timber product type for Vermont. Lighter colored bars indicate the 10-yr averages from 2007 to 2016, which were applied from 2017 through 2050. Data on commodity types is from the Vermont Harvest Reports (https://fpr.vermont.gov/forest/forest_business/forest_statistics/harvest_reports).

sequestration; therefore, $M < 0$ indicates that a given scenario sequesters more carbon than the baseline scenario. Our analysis accounts for "additionality" by comparing each scenario to the baseline according to the above equation. For the baseline and each alternative scenario, net emissions were estimated as the sum of emissions from the three forest sector components:

$$E = F + P + D$$

where $E$ is the net GHG emissions, $F$ is the net emissions from the forest ecosystem, $P$ is the emissions from the products sector (including bioenergy and landfill emissions), and $D$ is the displaced emissions from substituting wood for bioenergy and other materials.

The baseline scenario assumed that the mean disturbance and management regimes (e.g., harvest rates) and land-use change rates during the past 10 yr for which each data set is available, continued unchanged through the projection period (approximately 2017–2050, depending on the data set). Mitigation scenarios were implemented during the last 30 yr of the projection period (i.e., from 2020 through 2050).

### *Uncertainty analysis*

We estimated uncertainty in mitigation (scenario emissions minus baseline emissions) for each component of the forest sector: the forest ecosystem, the harvested wood products (HWP) sector, energy displacement, and product displacement. The uncertainty analysis is described in detail in Appendices S1.7–S1.9 and is briefly described here. For the forest ecosystem, we used a Monte-Carlo-based uncertainty approach following Metsaranta et al. (2017). For the HWP component, we used the CBMF-HWP modeling framework to simulate three separate half-life cases (low, medium, and high product retention times). Similarly, we evaluated a range of substitution benefits by simulating three separate energy displacement factors (DFs) and three separate product DFs (low, medium, and high). We used a Monte Carlo approach to combine the four component uncertainties to estimate the distribution of cumulative (year 2050) total mitigation for each scenario relative to baseline.

## Results

### *Baseline carbon trends*

In 2015, Vermont's forest sector sequestered approximately 4.5 million metric tons (4.5 Tg) of $CO_2e$ (Fig. 3), which is equivalent to the annual emissions from about 970,000 passenger vehicles; this assumes that a typical passenger vehicle emits about 4.6 metric tons of carbon dioxide per year, and that a typical gasoline vehicle has a fuel economy of about 22.0 miles per gallon (9.35 km/L) and drives around 11,500 miles per year (18,507 km; US EPA 2018). This carbon sequestration in 2015 was mostly due to the carbon uptake and storage by forest ecosystems (i.e., forest growth), which account for the sequestration of 4.2 Tg $CO_2e$ (negative net emission in Fig. 3). Product and energy substitution displaced another 1.5 Tg $CO_2e$. In contrast, the harvested wood products (HWP) pool was a net source, resulting in the emission of 1.2 Tg $CO_2e$ in 2015 to the atmosphere (positive net emission in Fig. 3) due to emissions from the decay of retired products and burning of bioenergy

TABLE 1. Indicators for the 11 scenarios for Vermont.

| Scenario number | Scenario name | Description | Parameters changed |
|---|---|---|---|
| 1 | short rotation, bioenergy | Increase harvests and reduce minimum harvest age. All additional harvested wood used for bioenergy. | harvest removals: +10%, minimum harvest age reduced from 80 to 70 yr, HWP proportions: additional harvested wood used for bioenergy |
| 2 | short rotation, all products | Increase harvests and reduce minimum harvest age. Timber product proportions are maintained for additional harvested wood. | harvest removals: +10%, minimum harvest age reduced from 80 to 70 yr, HWP proportions: no change |
| 3 | extend rotation | Extend the length of harvest rotation, reduce harvest removals. | harvest removals: −10%, minimum harvest age increased from 80 to 90 yr, HWP proportions: no change |
| 4 | reduce deforestation† | Reduce the annual area deforested to zero for public lands and cut by half for private lands. | deforestation rate reduced by: −16 ha/yr National Forest −104 ha/yr Other Public −50% (−373 ha/yr) Private |
| 5 | no net loss | Increase afforestation to equal deforestation rates across each ownership. | afforestation rate increased by: +5 ha/yr National Forest +24 ha/yr Other Public +658 ha/yr Private |
| 6 | residues | Increase harvest residues collected by increasing proportion of whole tree methods. Additional residues are used for bioenergy. | residues recovered (%) increased by: +9% for partial harvest +17% for shelterwood +20% for clearcut HWP proportions change: additional residues used for bioenergy |
| 7 | productivity | Increase productivity of existing young stands through silvicultural activities. | volume curves increased by +15%, area affected: 500 ha/yr on private land |
| 8 | insects | Increase area affected by moderate-severe insects. Salvage affected stands. | area affected by insects: +500 ha/yr, area salvaged: +500 ha/yr |
| 9 | portfolio | Combine the extend rotation, residues, and productivity. | harvest removals: 10%, minimum harvest age increased from 80 to 90 yr, residues recovered (%) increased by: +9% for partial harvest +17% for shelterwood +20% for clearcut, volume curves increased by +15% (500 ha/yr on private land) HWP proportions change: additional residues used for bioenergy volume curves increased by +15% (500 ha/yr on private land) |
| 10 | longer-lived products (LLP) | Increase the proportion of harvested wood for LLP at the cost of pulp and paper. | HWP proportions change: LLP +10% pulp and paper −10% |
| 11 | increase bioenergy | Increase the proportion of harvested wood for bioenergy at the cost of pulp and paper. | HWP proportions change: bioenergy +10% pulp and paper −10% |

*Notes:* The parameter changes are relative to a moving baseline scenario and all scenarios are implemented from 2020 to 2050. See Appendix S1: Section S3 for further descriptions of scenarios. HWP, harvested wood products.
†Deforestation is the permanent conversion of forest to a non-forest land use, such as development or agriculture. Harvesting followed by regeneration (artificial or natural) is not classified as deforestation.

(Appendix S1: Section S5, Fig. S4). As mentioned in *Datasets and modeling framework*, following the Canadian approach to forest sector carbon accounting, we do not assume that carbon is lost to the atmosphere from the forest ecosystem when it is harvested, but rather emissions from harvesting occur when the products are retired and are thus tracked in the HWP sector (Fig. 3). Appendix S1.4 explores the impacts of assuming instantaneous oxidation of harvested carbon from the ecosystem. Considering carbon stocks, the state's forests stored an estimated 500 Tg C (1,835 Tg $CO_2$e) in 2015 (Fig. 4). Wood products harvested in the state (in use and landfill) stored another 33 Tg C (121 Tg $CO_2$e) (Fig. 4, Appendix S1: Section S5, Fig. S5), accounting for an estimated 6% of the total carbon storage in the Vermont forest sector.

Throughout the historical period (1995–2016) and projection period (2017–2050) for the baseline (BAU) scenario, the Vermont forest sector (all components combined) maintained a net sink (negative net emissions) of carbon dioxide equivalent ($CO_2e$), although the strength of the sink declined over time and approached zero net emissions by 2050 (Fig. 3). The forest ecosystem accounts for the largest component of the forest sector net carbon balance and is the main driver of these trends.

Disturbances and harvesting did not have a strong effect on the overall declining C sink trend. The only detected disturbance during the historical period were insect outbreaks, which affected on average 32 ha/yr. While insects and pests such as the emerald ash borer (EAB) are a threat in Vermont, EAB was only detected in the state in 2018, and ash (*Fraxinus*) is a minor component of most Vermont forests, thus the effects have not been substantial. On the other hand, timber harvesting was more prominent, affecting approximately 35,000 ha of forest (~2%) per year. Years with greater harvested removals (e.g., in early 1990s) generally resulted in an increase in ecosystem emissions, when considering the ecosystem alone (Appendix S1: Section S4, Fig. S3). However, emissions associated with product use and retirement have generally been offset by forest growth and substitution when accounting for all components together (Fig. 3).

The decline in the forest sector carbon sink is primarily due to aging stands and the associated decline in net volume increment of late successional forests (Fig. 1b; Harmon 2001, Malmsheimer et al. 2008). Forests in Vermont currently consist of mostly middle to older age stands (Fig. 1a), which reflect regrowth after high rates of historical timber harvesting and reversion of agriculture back to forest in the early to mid 20th century. Under the baseline (BAU) scenario, relatively low disturbance and harvesting rates will continue; therefore, Vermont forests will continue on an aging trajectory through 2050 (Appendix S1: Section S6, Fig. S6), and ecosystem carbon stocks are projected to continue to approach a steady state (Fig. 3).

Land use change also affects forest carbon trends in Vermont under the baseline (BAU) scenario, but to a lesser extent than aging. The NLCD data sets from 1992 to 2011 indicate that, on average, the state lost about 1,119 ha/yr of forestland and gained about 256 ha/yr for a net loss of 863 ha/yr, with most of the changes taking place on private land. If there had been no deforestation between 1995 and 2015, cumulative ecosystem carbon sequestration by 2015 would have been approximately 11% higher during this 20-yr period (Appendix S1: Section S4, Fig. S3).

### *Mitigation scenarios*

The 11 scenarios varied widely in their mitigation potential, including both increases and decreases in net emissions relative to the baseline (BAU) scenario (Figs. 5 and 6, Figs. A.7 and A.8). Scenarios that targeted only the use of harvested wood but did not alter harvest rates had relatively strong mitigation potentials. For instance, the increase LLP scenario ranked first, reducing cumulative net emissions by 9.3 Tg $CO_2e$ or 14% by 2050 relative to the baseline emissions (Fig. 5). This scenario reduced emissions by increasing HWP half-lives and by

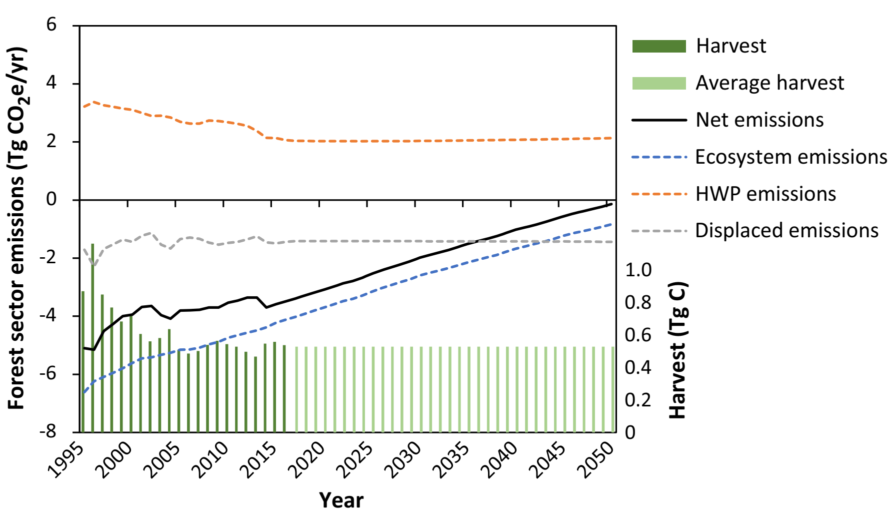


Fig. 3. Modeled annual $CO_2e$ balance for the Vermont forest sector. Net emissions (black) is the sum of sequestration from the forest ecosystem, emissions from HWP sector, and displaced emissions from substituting wood products for other emission intensive materials and fossil fuels (left axis). The historical harvest removals, Tg C/yr, are shown by the dark green bars and the 10-yr average (2007–2016) harvest is shown by the light green bars (right axis). To avoid double counting harvesting emissions, all emissions from harvesting from the ecosystem are tracked in the harvested wood products (HWP) sector, rather than as removals from the ecosystem. See Appendix S1: Section S4, Fig. S3 for forest ecosystem emissions by land use classes.

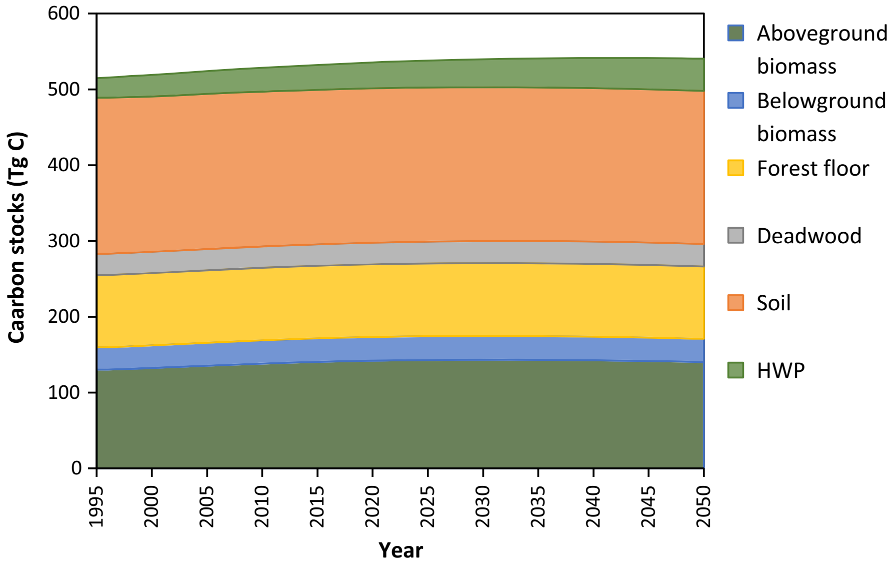


FIG. 4. Modeled forest sector carbon storage in Vermont. HWP storage accounts for both products in use and in landfills. Derived from CBM-CFS3 (ecosystem) and the CBMF-HWP (HWP).

displacing more emission-intensive building materials (Fig. 6). The other HWP-only scenario, *increase bioenergy,* ranked third, with a cumulative reduction in emissions of 4.9 Tg $CO_2$e (7.3%) by 2050. Although this scenario caused a small increase in HWP emissions by shortening product lifetimes, these additional emissions were more than offset by substitution benefits.

Combining multiple beneficial scenarios together also had a strong mitigation benefit. The *portfolio* scenario ranked second, reducing cumulative net emissions by 8.4 Tg $CO_2$e (12%) by 2050. This scenario combined three other scenarios: (1) *residues* (increase collection of harvest residues for bioenergy), (2) *extend rotation* (reduced harvests by 10% per year, increased harvest age by 10 yr), and (3) *productivity* (increase volume vs. age curves by 15%), each of which were effective alone. For example, increasing the collection of harvest residues for bioenergy use resulted in a net reduction of emissions of 4.0 Tg $CO_2$e (6%) by 2050. This scenario reduced forest ecosystem emissions because those residues would have otherwise decayed on the forest floor resulting in emissions to atmosphere. Also, although this scenario increased HWP emissions due to bioenergy production, these HWP emissions were offset by substitution (reduced fossil fuel emissions; Fig. 6). Likewise, *extending rotations* alone reduced net emissions by 5.3% (3.5 Tg $CO_2$e) by 2050. Extending harvest rotations results in a strong reduction in ecosystem emissions by increasing carbon stocks in live trees relative to the baseline scenario. *Extending rotations* also reduces HWP emissions, due to increased residence time of products and because fewer products are produced and retired; however, substitution benefits due to product and energy displacement are also reduced (Fig. 6). Last, increasing *productivity* alone had a small positive cumulative mitigation benefit on the forest ecosystem of 1.5 Tg $CO_2$e (2.2%) by 2050.

Land use change scenarios, which only affected the forest ecosystem, had moderate mitigation potentials. *Reducing deforestation,* which eliminated deforestation on public lands and cut private land deforestation in half, resulted in a projected reduction in net emissions of 4.1 Tg $CO_2$e (6.1%) by 2050. The *no net loss* scenario, which increased afforestation rates to equal deforestation, reduced cumulative emissions by 4.5% (3.0 Mt $CO_2$e).

Several scenarios caused projected increases in cumulative emissions. Shortening harvest rotations increased the amount of wood harvested annually by 10%. If additional harvested wood followed historical commodity proportions (ShortRotation in Figs. 5 and 6), emissions are projected to increase by 2.7% (1.8 Tg $CO_2$e). In contrast, if all additional harvested wood is used for bioenergy (ShortRotationBioE in Figs. 5 and 6), emissions are projected to increase by 5.5% (3.7 Tg $CO_2$e) by 2050. Both short-rotation scenarios result in equal losses in ecosystem carbon sequestration due to harvesting more live trees. However, using all additional harvested wood for bioenergy (ShortRotationBioE) has lower substitution benefits relative to HWP emissions compared to historical HWP use (ShortRotation; Fig. 6).

Last, we evaluated the effects of *insect* outbreak scenario given that a warming climate is projected to increase the risk of insects. If forest insects such as the emerald ash borer (EAB) affect an additional 500 ha of forest a year, but all killed trees are salvaged, outbreaks are projected to result in a small cumulative increase in

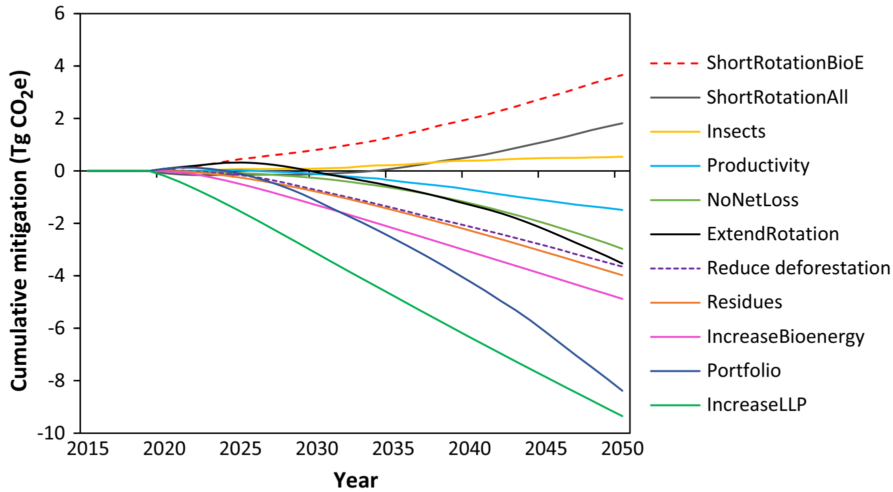


Fig. 5. Time series of the total cumulative mitigation relative to the baseline (BAU) for each scenario for Vermont. Negative values denote a reduction in greenhouse gas (GHG) emissions relative to baseline. LLP, longer-lived products.

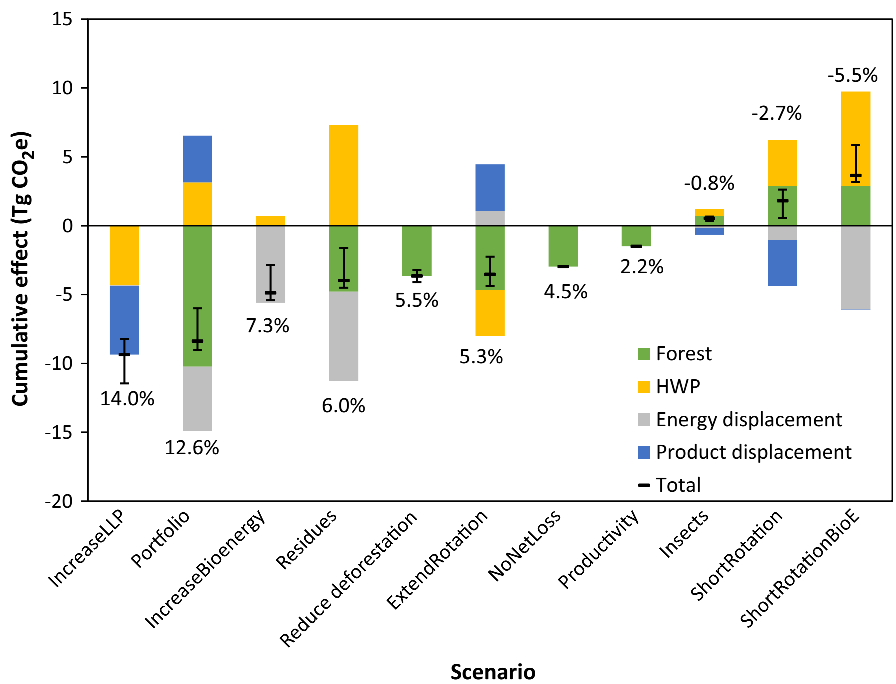


Fig. 6. Cumulative mitigation by component in 2050 for each scenario in Vermont ranked from highest to lowest total net mitigation (black dash) from left to right. Negative values denote a reduction in GHG emissions relative to the baseline (BAU) scenario. Mitigation for each component is based on the most likely parameter values (Appendix S1: Section S8, see Fig. S7 for component uncertainties). Total mitigation (black lines) is the sum of the component values, and uncertainty in total mitigation (error bars: 95% confidence interval) combines uncertainty from all components (Appendix S1: Section S8).

emissions of 0.5 Tg $CO_2$e (0.8%) by 2050. However, when compared to the baseline, any level of additional disturbance is expected to increase emissions.

The results of the uncertainty analysis indicate that energy and product displacement factors constitute the largest source of uncertainty of the mitigation potential of each scenario and can even impact the ranking of scenarios. However, the increase LLP scenario followed by the portfolio scenario result in the greatest mitigation potential across all DF levels assessed here. The uncertainty analysis and results are described in greater detail in Appendices S1.7–S1.9.

## Discussion

### *Baseline stocks and emissions*

Projected carbon trends under a baseline ("business as usual" or BAU) scenario indicate that Vermont's forest sector carbon sink will weaken over time and become nearly neutral (zero net emissions) by 2050. Generally, forests exhibit higher net volume increment when they are young to middle age as gains (growth) are larger than losses (mortality; e.g., Fig. 1b). Later in succession, the net volume increment declines to zero as losses increase and come into balance with gains. After decades of regrowth and recovery, many of Vermont's forests are reaching older stages of development (e.g., Fig. 1a), driving this decline in the rate of carbon accumulation and the strength of the forest carbon sink. Results here and elsewhere indicate that this age-related decline in carbon sequestration is likely to continue, which could bring about a national-scale decline in the strength of the carbon sink (Turner et al. 1995, Hurtt et al. 2002, Birdsey et al. 2006, Wear and Coulston 2015). Although the rate of carbon sequestration may be declining, ecosystem carbon stocks may increase for many decades even in older forests, because dead organic matter and soil carbon pools continue to accumulate (Luyssaert et al. 2008, Hoover et al. 2012, Zhou et al. 2015).

While historical changes in land use and forest management have been largely responsible for Vermont's forest carbon sink, recent declines in forestland have also contributed to the decline in the sink. This loss in forestland seen throughout the northeastern United States. is mostly attributed to suburban and rural residential sprawl (Foster et al. 2010). Remotely sensed NLCD data used in this study indicate that net loss of forestland in Vermont is relatively low, about 0.05% of the total forested area annually, similar to other estimates for the state (Foster et al. 2010, Olofsson et al. 2016). Though relatively small, this loss indicates a potential reversal of decades of forest expansion and carbon accumulation. However, recent economic-based projections indicate that forest loss in the Northeast and across the United States is expected to increase over the next few decades due to continued development pressures, particularly from urbanization (Radeloff et al. 2012, USDA Forest Service 2016). If deforestation rates increase as projected, Vermont's forest sector could shift to a carbon source before 2050, rather than reaching a steady state. Continued loss of forestland in the United States and globally may make it difficult to maintain net negative emissions into the second half of the century.

### *Mitigation analysis*

Over the 30-yr timespan of the mitigation analysis (2020–2050), several scenarios reduced emissions (i.e., a net climate-mitigation benefit), while a few scenarios resulted in greater emissions (Fig. 6). Increasing the proportion of wood used for long-lived wood products had the highest mitigation potential in this analysis, a 14% reduction in emissions (relative to the baseline, BAU) by 2050. Even when assessing a lower product DF, the increase LLP scenario continued to outperform others (Appendix S1: Section S8). By increasing product lifetimes, end-of-life emissions associated with retiring products are delayed, reducing HWP emissions. Using wood as a primary building material also has substantial substitution benefits by permanently displacing more fossil fuel intensive materials such as steel and concrete. These substitution benefits continue to accumulate over time with each harvest (Lippke et al. 2011, Lundmark et al. 2014). Several other studies have found that increasing product lifetimes, while keeping harvest levels constant, is an effective strategy for reducing emissions (Werner et al. 2010, Smyth et al. 2014, 2018, Lundmark et al. 2016, Dugan et al. 2018). A life cycle analysis found that the carbon footprint of wood-framed homes were 26% lower than steel-framed homes and 31% lower than concrete-framed homes (Bowyer et al. 2004).

Demand and markets for innovative, long-lived wood products such as mass timber have been on the rise in North America in recent years (Connolly et al. 2018). In addition to reducing emissions, mass timber has other benefits such as improved fireproofing and durability, ease and speed of construction, and boosting regional and rural economies (Robbins 2019). If waste wood that would otherwise decay on-site is used for mass timber, there could be an additional climate benefit. However, increasing the use of LLP like mass timber will require shifts in consumer preferences and landowner, builder, architect, and manufacturer behaviors (Steele 2015), as well as building more mass timber manufacturing plants.

The effectiveness of bioenergy scenarios here and in other studies has largely depended on the feedstock and alternative fates of the wood (Birdsey et al. 2018). Shifting the product mix to more bioenergy reduced net emissions in this study (increase bioenergy scenario) because the product mix shifted from a relatively short-lived product (pulp and paper) to an even shorter-lived product (bioenergy), which increases HWP emissions slightly. However, bioenergy use has substitution benefits, whereas the pulp and paper were assumed to have no substitution benefits. Conversely, using LLP like saw logs for bioenergy would increase net emissions because product lifetimes are significantly shortened (Dugan et al. 2018). While possible, the conversion of high value saw logs to low value biomass feedstocks is not typically an economically rational decision for managers. If the demand for pulp and paper or saw logs is inelastic, shifting product mixes within Vermont would lead to compensatory importation of wood products from outside the state; i.e., a so-called "leakage effect" (Malmsheimer et al. 2008).

Utilizing additional harvest residues for bioenergy (residues scenario) also reduced net emissions, which is consistent with other studies (Gan and Smith 2007, Lamers and Junginger 2013, Lamers et al. 2014, Smyth et al. 2017, Dugan et al. 2018). Rather than wood residues being left to decompose on-site or piled and burned (Smyth et al. 2017), using them for bioenergy transfers the emissions to the HWP sector, but then also has energy substitution benefits assuming less fossil fuel use. This scenario is achieved by increasing the proportion of whole-tree logging systems. In some cases, whole-tree logging has been avoided or even restricted to ensure site productivity and adequate nutrient loads after harvesting (Walmsley et al. 2009). However, whole-tree harvest operations have been found to leave a sufficient quantity of residues on site, averting losses to stand productivity (Premer et al. 2019).

Of all bioenergy scenarios, increasing harvests for bioenergy (short rotation bioenergy scenario) performed worst and resulted in a 5.5% increase in net emissions. The loss of live tree carbon from the ecosystem, which is emitted to the atmosphere via biomass burning, creates a carbon debt that must be re-paid before any mitigation benefits are realized (Ter-Mikaelian et al. 2015, Buchholz et al. 2016, Birdsey et al. 2018). Similarly, shortening the rotation but using additional harvested wood for all products, not just bioenergy (short rotation scenario) also increased emissions. Although increased harvest rates for bioenergy or other HWP may provide mitigation benefits in the long-term (e.g., at least a full rotation period), these benefits are not realized within the 30-yr time period of our mitigation analysis.

In contrast to the carbon debt created by increased harvest rates, extending rotations results in mitigation benefits in the short-term, as illustrated here and in other studies (Euskirchen et al. 2002, Li et al. 2007, McKechnie et al. 2010, Nunery and Keeton 2010, Ter-Mikaelian et al. 2011, Smyth et al. 2014, Dugan et al. 2018, Gunn and Buchholz 2018). Although extending rotations accrues carbon benefits in the ecosystem and HWP sector due to lower removals and product emissions, less wood means lower substitution benefits. Other studies found that more extreme no-harvest scenarios resulted in the highest total carbon storage in the ecosystem and products pools, but these generally did not evaluate substitution effects (e.g., Nunery and Keaton 2010, Pukkala 2017), which can be significant as found here. Extending rotations or eliminating harvesting all together also has economic trade-offs, such as lost revenue due to reduced harvesting and wood supply. However, under an extended rotation, the volume of final felling would be conceivably larger, thus eventually having an economic benefit, though delayed (Roberge et al. 2016). Extending rotations within Vermont could lead to leakage, or an unanticipated increase in timber harvesting outside of the state to fill the market gap and demand for wood. This leakage could subsequently reduce actual carbon benefits, and potentially cause a permanent loss of markets for Vermont producers if purchasers decide to stay with newly discovered supply chains. Likewise, in areas prone to disturbances such as wildfire, insects, disease, or deer browsing, extended rotations or abandoning harvesting could increase disturbance risk, which could reverse mitigation potential (Roberge et al. 2016, Smyth et al. 2018).

Given the potential for increased land use pressures on Vermont's forests and the strong impact of forest loss on carbon sequestration, scenarios that target land use change may become increasingly important in the state. Reducing the deforestation rate is a relatively cost-effective way to reduce emissions both in the short-term and long-term. Likewise, reforesting or afforesting lands (no net loss scenario) offers an effective climate solution nationally and globally. However, afforestation can involve trade-offs with alternative land uses, is generally more expensive than avoiding deforestation, and requires additional time for stands to establish and grow (Griscom et al. 2017, Fargione et al. 2018, Bastin et al. 2019).

Combining multiple effective scenarios can yield large carbon benefits and may also be more representative of the multiple outcomes that forest managers often intend to achieve. For example, the portfolio scenario, which combined the extending harvest rotation, residues for bioenergy, and increase in productivity scenarios, ranked second in this study, collectively reducing net emissions by 12% by 2050. Other scenarios that are non-interactive could also be additively combined. For example, combining the deforestation scenario with the increase LLP scenario, could potentially reduce net emissions by 12.9 Tg $CO_2$e (19.5%) by 2050.

### *Limitations and uncertainty*

All results and conclusions presented here are approximations that are contingent on the models, data, and scenario assumptions. We have quantified uncertainty in differences between each mitigation scenario and the baseline, by evaluating the uncertainty of each forest sector component alone as well as the combination of these uncertainties (Fig. 6; Appendices S1.7–S1.9). Uncertainty in energy and product displacement factors (DFs) dominate the total uncertainty, based on our primary set of assumptions. Energy DFs may vary based on population, energy demand, the type of fuel displaced, and accessibility to forests (Smyth et al. 2017, 2018, Köhl et al. 2020). Given that there are no coal-fired plants in Vermont, the low energy DF scenario may be more likely for the state. Likewise, product displacement varies regionally depending on technology efficiency, energy production systems, and post-consumer treatment of wood (e.g., burning for bioenergy, landfill; Leskinen et al. 2018).

The DFs are also uncertain as it is difficult to ascertain exactly which alternative products or fuels will be replaced by wood-based products or energy (Soimakallio et al. 2016), or if they will be replaced at all. For instance, if production of LLP increases in Vermont, it is unclear whether wood will substitute for concrete buildings in the state or be exported to states with higher wood demand. Policy shifts incentivizing the use of locally produced wood may be necessary to reach the full potential of substitution benefits. As previously mentioned, reducing the wood supply (extend rotation scenario) could cause leakage outside of the state. However, this would suggest that there is no substitution of wooden buildings by concrete or steel, but merely a shift in supply of the wood, further highlighting the uncertainty around displacement. Additional research evaluating the regional and market-level substitution impacts and feasibilities are needed.

The data sets selected and their inherent uncertainty may also affect results. Remotely sensed land cover products like NLCD may overestimate forest loss by classifying stand-replacing disturbances or clear-cut harvests as permanent forest cover losses (Nelson and Reams 2017). To minimize this potential, we constrained the NLCD product by omitting changes of forestland to or from grassland or scrub/shrub, as these were assumed to represent temporary forest transitions (i.e., harvests or disturbance), which in some cases could also result in omissions of real LUC. Estimated rates of LUC may also vary by data source. For instance, the FIA data for Vermont indicates that between 2007 and 2012 the state saw a net gain of about 2,500 ha of forestland (Morin et al. 2015), whereas the constrained NLCD data used in this study indicates a net loss in forestland of about 3,400 ha. However, during more recent years (2012–2016), the FIA data indicates a sharp decrease in forestland of 35,000 ha. At the time of this project the NLCD 2016 data set had not yet been released. The FIA data may contain an inherent lag in detecting disturbances and LUC as plots are only remeasured every 5 yr (e.g. Dugan et al. 2017).

Our modeling approach was designed to evaluate the carbon mitigation potential of different management scenarios, but we did not consider social or economic factors, which could reduce the actual mitigation likely to be achieved by some scenarios (Lemprière et al. 2017). The scenarios we evaluated were all considered to be technically feasible, but there remain uncertainties regarding costs and regulatory or market barriers that could affect their implementation. While forest and product managers often have multiple management objectives, economic forces will likely play a significant role in determining the range of management scenarios that are likely to be implemented, especially on private lands.

## Conclusion

The strength of the forest sector carbon sink in Vermont has been declining and is projected to continue to decline throughout 2050 under a baseline (BAU) scenario and 11 alternative mitigation scenarios. However, our model results suggest that there are effective management actions that would reduce net emissions in Vermont relative to the BAU scenario, thereby mitigating the (likely unavoidable) weakening of the state's C sink over the next 30 yr. This study can serve to inform Vermont Forests, Parks & Recreation officials and other policy makers on potential carbon outcomes of alternative management scenarios. However, carbon sequestration is just one of the many ecosystem services for which forests and their products are managed. Enhancing forest sector carbon sequestration can come with important trade-offs. Thus, this study may be used as a component of trade-off analyses and risk assessments to identify knowledge gaps, support evidence-based policymaking, and weigh the costs and benefits of alternative scenarios and outcomes for different stakeholders.

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## Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2327/full

## Data Availability

Data (Dugan et al. 2021) are available from the U.S.D.A. Forest Service Research Data Archive: https://doi.org/10.2737/RDS-2021-0018.