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ARTICLE

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Net carbon sequestration implications of intensified timber harvest in Northeastern U.S. forests

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Abstract
U.S. forests, particularly in the eastern states, provide an important offset to greenhouse gas (GHG) emissions. Some have proposed that forest-based natural climate solutions can be strengthened via a number of strategies, including increases in the production of forest biomass energy. We used output from a forest dynamics model (SORTIE-ND) in combination with a GHG accounting tool (ForGATE) to estimate the carbon consequences of current and intensified timber harvest regimes in the Northeastern United States. We considered a range of carbon pools including forest ecosystem pools, forest product pools, and waste pools, along with different scenarios of feedstock production for biomass energy. The business-as-usual (BAU) scenario, which represents current harvest practices derived from the analysis of U.S. Forest Service Forest Inventory and Analysis data, sequestered more net CO_2 equivalents than any of the intensified harvest and feedstock utilization scenarios over the next decade, the most important time period for combatting climate change. Increasing the intensity of timber harvest increased total emissions and reduced landscape average forest carbon stocks, resulting in reduced net carbon sequestration relative to current harvest regimes. Net carbon sequestration "parity points," where the regional cumulative net carbon sequestration from alternate intensified harvest scenarios converge with and then exceed the BAU baseline, ranged from 12 to 40 years. A "no harvest" scenario provides an estimate of an upper bound on forest carbon sequestration in the region given the expected successional dynamics of the region's forests but ignores leakage. Regional net carbon sequestration is primarily influenced by (1) the harvest regime and amount of forest biomass removal, (2) the degree to which bioenergy displaces fossil fuel use, and (3) the proportion of biomass diverted to energy feedstocks versus wood products.

KEYWORDS
bioenergy, carbon sequestration, carbon storage, forest harvest regimes, Northeastern U.S. forests

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INTRODUCTION

Carbon sequestration in U.S. forests and forest products offsets approximately 11% of U.S. economy-wide greenhouse gas (GHG) emissions annually (Domke et al., 2020), and recent studies have highlighted opportunities to enhance the role of forests in climate mitigation (Drever et al., 2021; Fargione et al., 2018). Forests in the eastern half of the country contribute a disproportionate share of the nation's forest carbon sequestration. Domke et al. (2020) estimate that forestland in the 31 eastern United States contained ~59% of the estimated total forest carbon stocks but provided 85% of the net carbon sequestration for the 48 conterminous states in 2018 (Domke et al., 2020).

Land use history and disturbance regimes clearly play a role in the magnitude of the eastern forest carbon sink, and a significant fraction of the current forestland is the product of either afforestation of agricultural land abandoned during the past 200 years, or recovery following high rates of clearcutting in the late 19th and early 20th centuries. This has led to assumptions that forests of the region are even-aged and that rates of productivity and carbon sequestration will decline as those forests mature (e.g., Bradford & Kastendick, 2010; Hurtt et al., 2002; Turner & Koerper, 1995). Logging is by far the dominant disturbance in eastern forests (Brown et al., 2018; Canham et al., 2013), and some studies have proposed that increases in overall harvest regimes could increase net carbon sequestration in forests and forest products (e.g., Peckham et al., 2012). Both of these assertions have been challenged and are the subject of ongoing debate (Keeton, 2018; Keeton et al., 2011; McGarvey et al., 2015; Nunery & Keeton, 2010; Rhemtulla et al., 2009). Keeton et al. (2011) conclude that Northeastern U.S. forests have a substantial potential to sequester and store carbon late into succession (350–400 years). Studies that combine forest ecosystem processes with wood product life cycles suggest that decreasing harvest intensity increases carbon sequestration (Gunn & Buchholz, 2018; Nunery & Keeton, 2010).

There has also been interest in the development of forest biomass energy as a component of the renewable energy portfolio of the Northeastern United States (Milbrandt, 2008; Perlack et al., 2008). While often touted as an inherently "carbon-neutral" energy source, it has become clear that a wide range of factors need to be considered to evaluate the net carbon and climate impact of biomass energy production (Schulze et al., 2012; Zanchi et al., 2012). To achieve a reduction in GHG emissions, many bioenergy policies assume that the emissions resulting from bioenergy combustion are balanced by plant regrowth and sequestration. A growing body of literature examines whether burning woody biomass for energy has a net positive or net negative carbon impact (Birdsey et al., 2018; Buchholz et al., 2017, 2021; Dwivedi et al., 2019; Fargione et al., 2008; Gunn & Buchholz, 2018; Haberl et al., 2012; Malmsheimer et al., 2011; Mika & Keeton, 2013, 2015; Searchinger et al., 2009, 2017; Sterman et al., 2018; Ter-Mikaelian et al., 2015; Vance, 2018). Determining the actual impact of forest biomass energy on atmospheric carbon, however, should consider emissions from land use change when biomass is harvested or grown for energy (Fargione et al., 2008; Searchinger et al., 2008), the source of the energy feedstock and its alternative fate, the time horizons needed to account for the full life cycle of forest growth, energy emissions associated with wood product supply chains and fossil fuel substitution, and forest carbon cycles (Birdsey et al., 2018; Haberl et al., 2012; Ter-Mikaelian et al., 2015; Zanchi et al., 2012). Accurately accounting for these often-counteracting processes will determine the calculation of the net impact of forest biomass energy production on net GHG emissions or reductions.

In a separate study (Brown et al., 2018), we characterized the current forest harvest regimes for the major forest types of the northern forest states from New York to Maine. We then used SORTIE-ND, a spatially explicit individual-tree forest stand model (Coates et al., 2003; Forsyth et al., 2015; Uriarte et al., 2009), to project the effects of that regime and four alternative harvest regimes on forest structure, composition, and productivity over the next 150 years. Here, we take the results of that study and combine them with a simplified model of within-forest detrital carbon dynamics, and an analysis of the net carbon impacts (sequestration and emissions) of the flow of harvested wood through a range of forest products and biomass energy feedstocks. That analysis makes use of ForGATE, a forest-sector GHG accounting tool originally developed for the state of Maine (Hennigar et al., 2013). Specifically, we track forest ecosystem and harvested wood product carbon pools and a full suite of emissions including forest decomposition, energy emissions, and waste emissions. Our results allow us to project the net carbon sequestration of a broad range of forest harvest regimes and biomass energy production over the next 100 years in the four northern forest states, combining both carbon dynamics in forests as well as in forest products and landfills. Therefore, our analyses address two broad questions: (1) What are the effects of harvest intensification on forest and wood product carbon pools? and (2) What are the effects of harvest intensification on net forest carbon sequestration?

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METHODS

Study area

The study area comprises all the forestland as defined by the National Forest Inventory in the states of New York, Vermont, New Hampshire, and Maine, approximately 71% of the four-state region (USDA Forest Service, 2020). Forest types vary from boreal spruce–fir (*Picea* sp.–*Abies* sp.) forests to dry temperate oak–hickory (*Quercus* sp.–*Carya* sp.) forests, with temperate northern hardwood–conifer forests being the most widespread. The temperate climate is defined by cold, snowy winters and warm summers. The terrain is predominately postglacial hills with intermixed mountain ranges and coastal lowlands. Eighty percent of the forestland is owned by private owners. Most of these landowners are noncorporate (70%); however, industrial owners hold significant acreage particularly in Maine and northern New York (Thompson et al., 2017).

Timber harvest scenarios and implementation in SORTIE-ND

Our analyses compare five harvest scenarios that varied in magnitude and frequency of harvest, described fully in Brown et al. (2018) (Table 1). The first harvest scenario represents the current harvest regime and is the baseline for comparison (Brown et al., 2018). We used U.S. Forest Service Forest Inventory and Analysis (FIA) data to estimate current harvest regimes for six different forest types and regions in the study area: aspen-birch (*Populus* sp.–*Betula* sp.), spruce–fir (*Picea* sp.–*Abies* sp.), bottomland, oak–hickory (*Quercus* sp.–*Carya* sp.), northern hardwood–conifer forests in Maine, and northern hardwood–conifer forests in the remaining three states (New York, Vermont, New Hampshire) (Brown et al., 2018; Canham et al., 2013). For each of the six forest type/regions, Brown et al. (2018) quantified two components of the harvest regime: (1) the annual probability that a plot was harvested and (2) the total amount of basal area removed if a plot was harvested. The best statistical model characterized the annual probability of harvest as a function of forest type/region, total plot basal area, and distance to the nearest improved road. This harvest regime represents current practices and is the baseline harvest regime (H1) for comparison with the other regimes.

In addition to the current harvest regime (H1), four alternate harvest scenarios were examined (Table 1) (Brown et al., 2018). The second scenario increases average harvest intensity by 50% ("current harvest + intensity"; H2). The third scenario increases the frequency of harvests by 75%, keeping the current distribution of harvest intensity ("current harvest + frequency"; H3). The fourth scenario increases average harvest intensity by 50% and harvest frequency by 100% ("current harvest + intensity + frequency"; H4). For reference, a fifth scenario is a no harvest scenario ("no harvest"; H0).

TABLE 1 Harvest and biomass feedstock scenarios for the four-state study area of New York, Vermont, New Hampshire, and Maine (Brown et al., 2018).

Harvest or biomass energy feedstock scenario	Harvest or biomass energy feedstock scenario definition
No harvest (H0)	No harvest regime
Current harvest (H1)	The current harvest regime characterized as a function of forest type/region, total plot basal area, and distance to the nearest improved road, including a 3°C increase in mean annual temperature and a 10% increase in total annual precipitation over the next 100 years (Brown et al., 2018)
Current harvest + intensity (H2)	The current harvest regime and a 50% increase in average harvest intensity
Current harvest + frequency (H3)	The current harvest regime and a 75% increase in harvest frequency
Current harvest + intensity + frequency (H4)	The current harvest regime, a 50% increase in average harvest intensity, and a 100% increase in harvest frequency
Low feedstock (F1)	5% of hardwood and softwood sawlogs diverted to chip and pellet energy feedstocks; 20% of hardwood and softwood pulpwood diverted to energy feedstocks; 25% of logging residue diverted to energy feedstocks
High feedstock (F2)	20% of hardwood and softwood sawlogs diverted to chip and pellet energy feedstocks; 80% of hardwood and softwood pulpwood diverted to energy feedstocks; 50% of logging residue diverted to energy feedstocks

Note: With the exception of the no harvest scenario (H0), scenarios consist of one of the harvest options combined with either the low feedstock (F1) or high feedstock (F2) option.

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The five harvest scenarios were implemented in SORTIE-ND, a spatially explicit model of forest dynamics. SORTIE-ND follows individual seedlings, saplings, and adult trees over time through a sequence of behaviors, including the harvest regime (described above), tree growth and natural mortality, and seedling recruitment. For each harvest scenario, species structure and composition data from 5000 randomly selected FIA plots were used to initialize 5000 individual SORTIE-ND runs. Each run represents the predicted dynamics of a 4-ha forest stand. The simulations utilize the 30 most common species in the study area, which were parameterized from FIA data (Brown et al., 2018; Canham & Murphy, 2016a, 2016b; Canham & Murphy, 2017). Climate change was incorporated into all scenarios consisting of a 3°C increase in mean annual temperature and a 10% increase in total annual precipitation over 100 years followed by stabilization (Horton et al., 2014). Natural disturbances like ice storm damage and beech bark disease are included in the model to the extent that their impacts are picked up in FIA plot data; however, stochastic events are not explicitly incorporated. Outputs include detailed metrics of stand structure and composition, as well as the magnitude of harvest by species and tree size (dbh). SORTIE-ND partitions harvested biomass into six harvest product carbon pools according to U.S. Forest Service Timber Products Output (TPO) studies: softwood sawlogs, hardwood sawlogs, softwood pulp, hardwood pulp, softwood residues, and hardwood residues (Figure 1, column B). The no harvest scenario does not include harvested wood products so simply represents SORTIE-ND modeled forest dynamics (Figure 1, column A).

Bioenergy feedstock scenarios

To understand how changes in timber harvest affect net GHG emissions, we considered two bioenergy feedstock scenarios that determine the proportion of harvest products (Figure 1, column B) that are used as energy feedstocks, including logging residues, chips, and pellets (Figure 1, column C; Table 1). Logging residues from SORTIE-ND either stay in the forest and eventually decompose (Figure 1, columns A and B) or are used for one of the three energy feedstocks. We treat feedstock and energy pools as "pass-through" pools and assume there is no biomass feedstock storage and that the

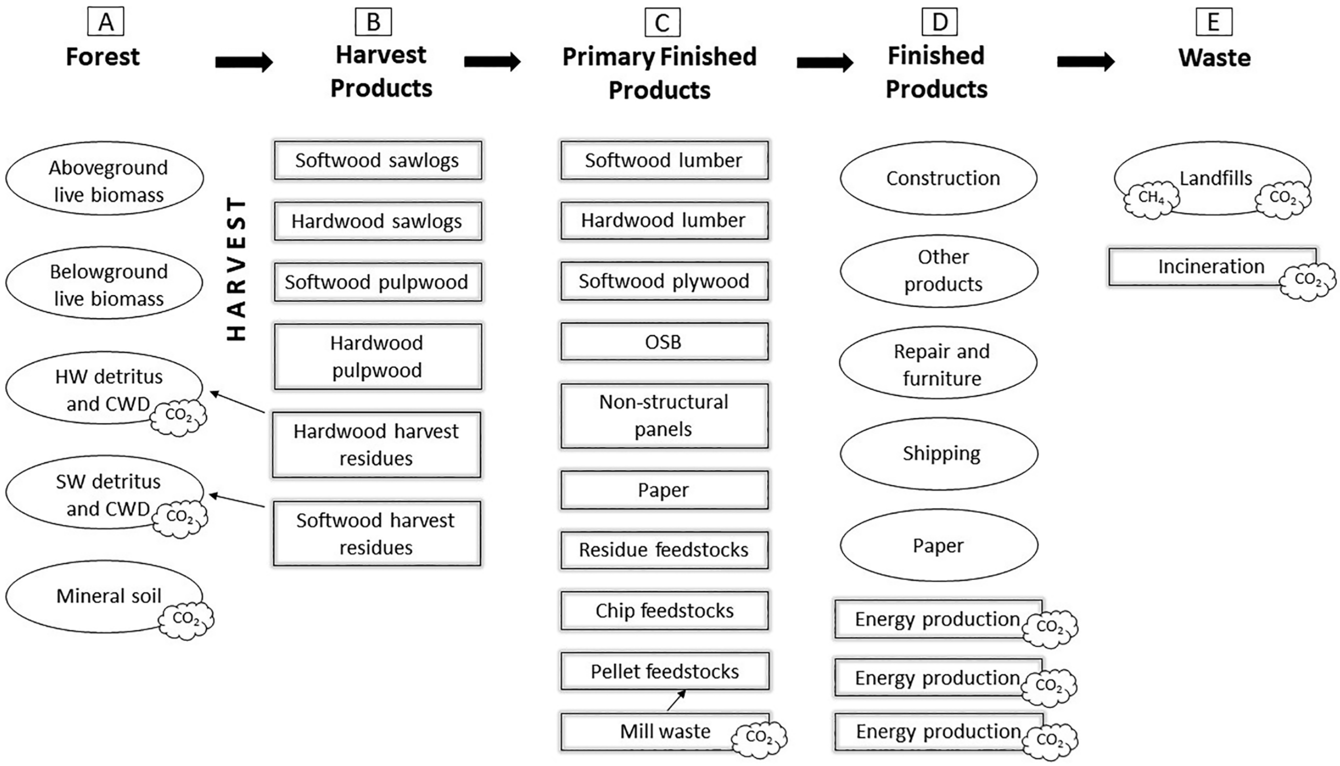

FIGURE 1 Carbon transfer from forest pools through waste pools and release to the atmosphere. Forest carbon (column A) is transferred to harvest products (column B) as defined by each harvest regime (Brown et al., 2018). Carbon in harvest product pools (column B) is transferred to end products, waste pools, or the atmosphere (columns C–E) based on ForGATE (Hennigar et al., 2013). Ovals indicate carbon pools that can accumulate or decline, rectangles represent annual pass-through pools, and clouds represent greenhouse gas emissions. CH_4, methane; CO_2, carbon dioxide; HW, hardwood; OSB, oriented strand board; SW, softwood.

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feedstock pools are completely diverted to energy production in the year of harvest. The first scenario (F1) diverts 5% of hardwood and softwood sawlogs, 20% of hardwood and softwood pulpwood, and 25% of logging residue to energy feedstocks ("low feedstock" scenario). The second feedstock scenario (F2) diverts 20% of hardwood and softwood sawlogs, 80% of hardwood and softwood pulpwood, and 50% of logging residue to energy feedstock ("high feedstock" scenario). In all scenarios, 25% of sawmill residues are used as pellet feedstock (Buchholz et al., 2017), and harvest residues are equally divided between pellet, chip, and residue feedstocks in the low and high feedstock scenarios. In total, eight scenarios representing alternative combinations of harvest (Table 1; scenarios H1, H2, H3, and H4) and feedstock scenarios (Table 1; scenarios F1 and F2) were considered. The ninth scenario is the no harvest comparison (H0), which does not generate energy feedstocks or other wood products (Table 2).

GHG accounting for wood products utilizing ForGATE

The output from the SORTIE-ND analyses of the effects of the different harvest regimes on forests and harvest levels reported in Brown et al. (2018) provided the inputs to our analyses reported here. Specifically, we used the forest carbon stocks and harvest data from SORTIE-ND (Figure 1, columns A and B) as inputs to calculate carbon storage and emissions associated with finished wood products and landfills, based on the ForGATE model of Hennigar et al. (2013) (Figure 1, columns C–E). Carbon in the pulpwood and sawlog pools is transferred to mill waste, energy feedstocks, and primary finished products (i.e., lumber, plywood, oriented strand board [OSB], nonstructural panels, and pulp/paper) (Figure 1, column C). From there, carbon is combusted as energy or transferred to five finished end-use product pools (i.e., construction materials, repair and furniture, shipping products, paper, and others) (Figure 1, column D). Finally, all remaining wood product pools end up in one of two waste stream pools: landfills or incineration (Figure 1, column E). Parameters such as product half-lives and mill efficiencies are described fully in ForGATE (Hennigar et al., 2013). We assume the harvest product pools and primary finished products are pass-through pools, meaning carbon is transferred through these pools in the year of harvest. Alternatively, the five finished end-use product pools can accumulate or lose carbon over time, functioning as long-term carbon storage. Carbon in these pools is transferred to the waste stream at a fixed percentage loss per year (Smith et al., 2006, in Hennigar et al., 2013). A fraction of the carbon is transferred to landfills, a sixth long-term carbon storage pool, and the remainder is incinerated and immediately released into the atmosphere (Figure 1, column E).

Net carbon sequestration calculation

We calculated 10 sources of carbon emissions from forest system dynamics (three emission sources) and the forest product sector (seven emission sources) (Figure 1, denoted by clouds). We only considered carbon dioxide (CO_2) emissions in forests but included methane (CH_4) landfill emissions. Forest CO_2 emissions result from the decomposition of hardwood and softwood detritus and mineral soil organic matter (Figure 1, column A). Detrital pools are comprised of standing and downed coarse woody debris (CWD), fine woody debris from branches, tops, and harvested residue, and belowground dead material like coarse and fine roots. To estimate initial hardwood and softwood detrital pool sizes (13.8 and 9.2 Mg C ha^{-1}, respectively), we used detrital pool estimates from Birdsey and Lewis (2003) and apportioned the values according to the relative abundance of live hardwood and softwood trees in forests of the study area (60% and 40%, respectively). We assumed annual

TABLE 2 Carbon pools in each harvest/feedstock scenario after 100 years (Mg C ha^{-1}).

Carbon pool	H0	H1F1	H1F2	H2F1	H2F2	H3F1	H3F2	H4F1	H4F2
Live trees	172.6	117.7	117.7	113.2	113.2	105.5	105.5	99.0	99.0
Coarse woody debris and detritus	60.5	50.5	49.6	49.5	48.5	48.0	46.9	47.2	45.9
Mineral soil	162.8	161.2	160.9	161.0	160.7	160.7	160.2	160.5	160.0
Forest products	0.0	8.7	5.5	9.3	5.8	10.3	6.1	11.1	6.2
Landfill	0.0	6.2	3.7	6.7	3.9	7.5	4.1	8.2	4.1
Total	396.0	344.3	337.5	339.8	332.0	332.0	322.8	326.0	315.3

Note: Descriptions of the harvest/feedstock scenarios are given in Table 1. All carbon pools include the initial condition for each pool (average Mg C ha^{-1} across the landscape at the start of each scenario) plus the accumulated carbon for 100 years, except the forest products pool. The forest products pool only includes accumulated carbon.

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decomposition rates of 0.069/year and 0.039/year for hardwood and softwood detrital pools, respectively (Russell et al., 2014; Tonitto et al., 2014) and diverted a fraction of carbon in the detrital pools (0.005/year) to the mineral soil pool each year (Crowley et al., 2016). We assumed a mineral soil pool decomposition rate of 0.00075/year (Tonitto et al., 2014) and an initial pool size of 151.95 Mg C ha^{-1} (Birdsey & Lewis, 2003).

The remaining seven carbon emission sources are from the forest products sector, via waste decomposition and incineration, mill waste combustion, and wood energy production (Figure 1, columns C–E). First, a fixed proportion of long-term forest products are diverted annually to the waste stream, with 19.6% of the waste stream incinerated and 80.4% sent to landfills (EPA, 2019). We assume the incineration pool is transferred immediately to the atmosphere as CO_2 emissions, whereas in landfills, the carbon pool can increase or decrease over time. Landfill forest carbon decomposes at a rate of 0.0495/year (Figure 1), and emissions include both CO_2 (54%) and CH_4 (46%) (Hennigar et al., 2013). We account for the proportion of landfill CH_4 emissions that are effectively captured (37%) (Hennigar et al., 2013). The initial landfill carbon pool is estimated to be 2.17 Mg C ha^{-1} of the forestland, based on Birdsey and Lewis (2003). Second, mill waste emissions (CO_2) are generated from the combustion of mill waste, after sawmill residues have been diverted to pellet feedstock. While many mills utilize cogeneration to produce electricity on site, we did not include that on-site energy as a part of the fossil fuel offset. We also assume complete combustion of the annual mill waste pool. The final three sources of forest product emissions (CO_2) are from wood bioenergy production (Figure 1, column D). We assume the energy pools (pellets, chips, and residues) are fully utilized during the year the feedstock is generated and transferred immediately into the atmosphere. Although the ForGATE tool allows users to account for manufacturing and harvest and transport emissions (Hennigar et al., 2013), we did not include these emissions here. Harvest and transport emissions are a small component of the total forest products sector emissions (Gunn & Buchholz, 2018). Manufacturing emissions can be more significant particularly from pulp and paper (Gunn & Buchholz, 2018); however, given the variability in electricity inputs and process heat sources between timber products, these emissions were not incorporated.

The 10 emission outputs in combination with sequestration estimates from the harvest scenarios are used to calculate net carbon impact (total sequestration − total emissions), where total sequestration equals gross forest growth plus the annual changes in the forest product and landfill pools, and total emissions equals the 10 summed emission sources. We define gross forest growth as the carbon removed from the atmosphere by forest growth, including net biomass increment plus natural mortality and harvested biomass. Net carbon sequestration is presented as an annual rate of change (total sequestration − total emissions).

Fossil fuel displacement scenarios

Finally, we examine six fossil fuel displacement scenarios, ranging from no offset to 50%, 60%, 70%, 80%, and 90% of fossil fuel emissions displaced. For an equal amount of energy production, we define fossil fuel displacement as the fossil fuel emissions that are supplanted by forest bioenergy emissions. Therefore, this flexible approach can account for any specific conversion technology efficiencies. Given the higher energy density and greater efficiency of fossil fuel utilization, each ton of CO_2 emitted from biomass feedstock combustion produces energy that could displace less than one ton of CO_2 emitted from fossil fuel combustion. For example, to produce 15 million GJ of energy, it takes roughly 1 million metric tons of forest biomass in the form of chip feedstocks utilized in a commercial boiler to produce industrial heat at a 75% efficiency. The same amount of energy would require approximately 403 million m^3 of natural gas. There are 1.8 million metric tons of CO_2 and 752,000 metric tons CO_2 emissions associated with combusting this quantity of woody biomass and natural gas, respectively. Therefore, woody biomass energy displaces 41% of fossil fuel emissions in this example.

To present the results, we converted CO_2 and CH_4 (using a 100-year global warming potential of 25) to a carbon dioxide equivalent value (CO_2e). Results are presented as a combination of harvest scenarios (H) and bioenergy feedstock scenarios (F), and, when applicable, include fossil fuel displacement scenarios in percent (Table 1). For example, H1/F1/50 is a scenario comprised of the current baseline harvest regime (H1) with low biomass feedstock utilization (F1), assuming 50% fossil fuel displacement by bioenergy. We refer to the H1/F1 scenario as the business-as-usual scenario (BAU).

All of our analyses were conducted in R version 4.1.2 (R Core Team, 2021), including recoding the ForGATE model from a spreadsheet format to R code capable of accepting SORTIE-ND input.

RESULTS

Predicted harvest effects on carbon pools

The cumulative amount of carbon stored in all pools is estimated to increase in every harvest/feedstock scenario

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over the 100-year period from 2020 to 2119 (Figure 2). Live tree biomass is the largest carbon pool in all scenarios and is projected to increase between 53.4% in the most intensive harvest regime (H4) and 102.4% in the no harvest scenario (H0). Across the 18.4-million hectares of forestland in New York, Vermont, New Hampshire, and Maine, an average of 50.0 Mg C ha^{-1} will accumulate between 2020 and 2119 based on the BAU scenario (H1/F1). The live tree and detritus carbon pools increase and stabilize after approximately 50 and 90 years, respectively, whereas the mineral soil, forest product, and landfill forest carbon pools increase steadily across the entire time period (Figure 2). The only exception to this pattern is the no harvest scenario (H0). Because no wood products are removed from the forest, the forest product carbon pool stays at zero, and the landfill forest carbon pool declines due to the decomposition in landfills in combination with no new wood product additions (Figure 2).

As harvest intensity increases, the amount of total carbon stored across all pools decreases. The most intensive harvest scenario (H4/F1) accumulates 13.2% less carbon during the 100-year period than the BAU scenario. Although the forest products and landfill pools are larger than those in the BAU scenario under the most intensive harvest scenario (27.7% and 48.8%, respectively), the proportion of stored carbon accumulated in forest pools (live trees, CWD, and forest floor detritus) declines from 92.3% in the BAU scenario to 80.2% in H4/F1. Thus, the decline in live and detrital biomass pools under more intensive harvests more than offsets the increases in forest products and landfill pools

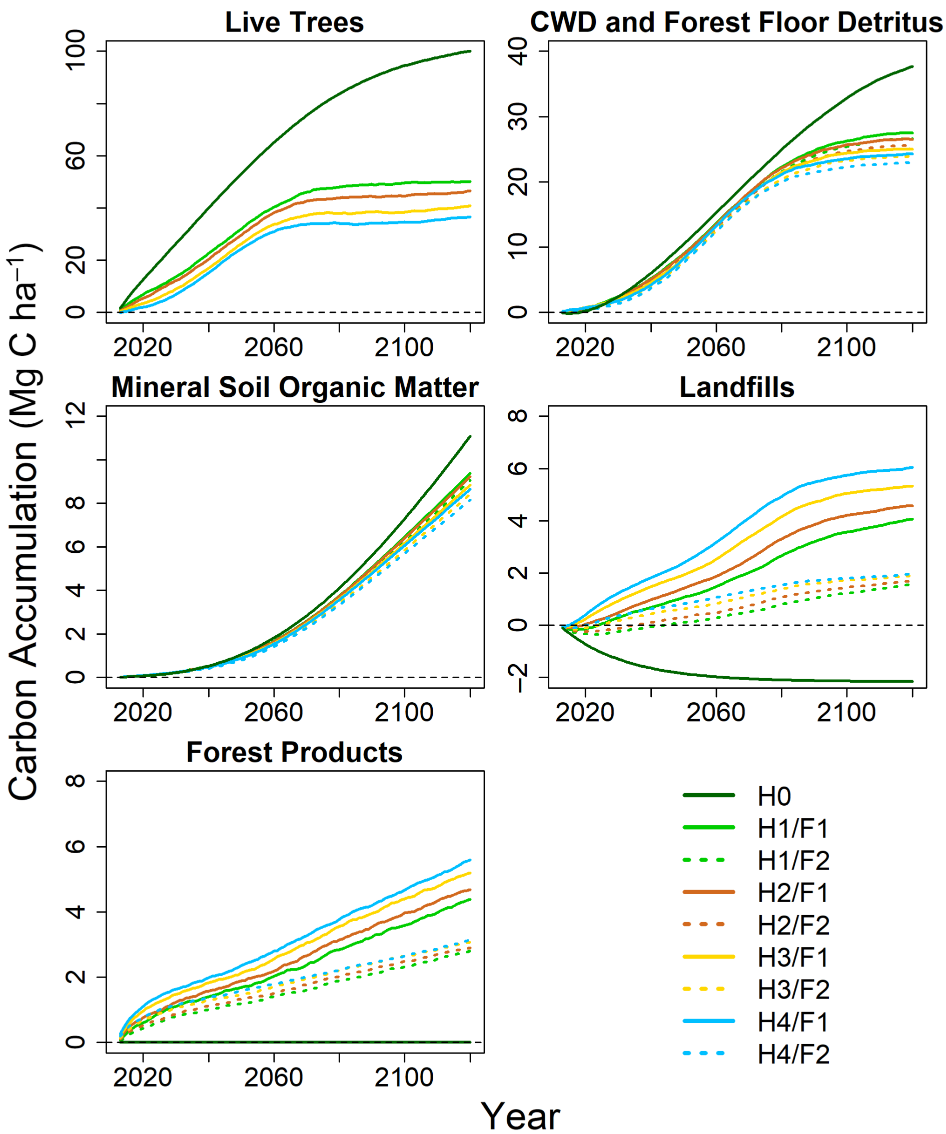

FIGURE 2 Carbon accumulation in all carbon pools over 100 years resulting from harvest (H) and feedstock (F) scenarios. The live tree panel shows overlapping results when the harvest scenarios are the same, but the feedstock scenarios differ. The harvest scenario determines the live tree biomass results, not the feedstock scenario. Refer to Table 1 for scenario definitions.

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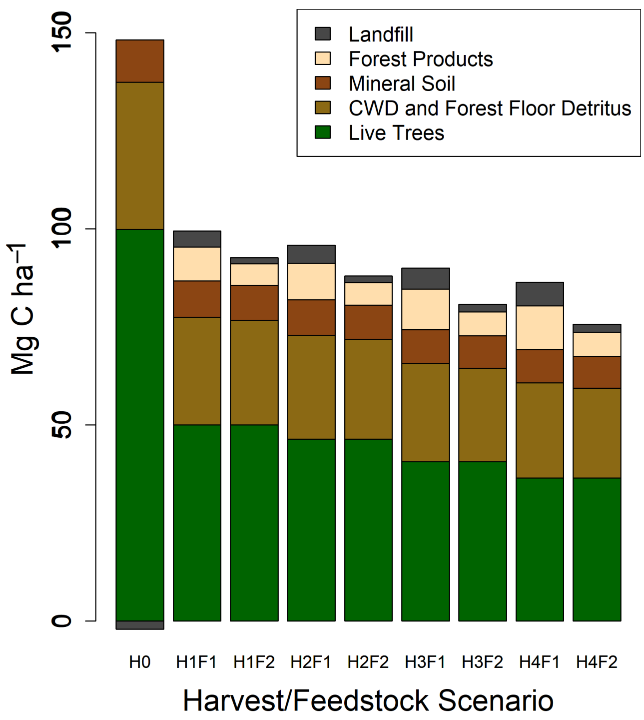

FIGURE 3 Total carbon stored in five pools—live trees, coarse woody debris (CWD) and forest floor detritus, mineral soil, forest products, and landfill forest carbon pools—after 100 years resulting from nine harvest (H) and feedstock (F) scenarios. Refer to Table 1 for scenario definitions.

(Table 2, Figure 3). Diverting additional harvested wood and residues to energy feedstocks further reduces the total amount of carbon stored in each harvest/feedstock scenario due to a reduction in the carbon additions to the forest floor detritus and mineral soil pools, as well as to the forest products and landfill forest carbon pools. The no harvest scenario (H0) predicts more accumulated carbon in live trees alone (99.9 Mg C ha^{-1}) than the total accumulated carbon pools in all other harvest/feedback scenarios (Figure 3).

As more harvest residue is removed from the forest and diverted to energy feedstocks, the forest floor and mineral soil pools accumulate less biomass across the landscape (Figure 4). After 100 years, the additional residue removals from the forest when comparing H1/F1 and H1/F2 are estimated to decrease carbon storage in the forest floor pool and mineral soil pool by 3.2% and 3.4%, respectively. While the percent decreases in these carbon pools appear relatively small, across the entire northern forest landscape, the carbon storage losses total 16.3 million metric tons of C. Reductions in detrital carbon pools are exacerbated further when intensifying harvest is combined with greater use of logging residues as energy feedstocks. Forest floor and mineral soil carbon pools decrease by 16.5% and 12.9%, respectively, when comparing the least intensive harvest and feedstock scenario (H1/F1) to the most intensive harvest and feedstock scenario (H4/F2) (Figure 4).

Predicted GHG implications of alternative harvest regimes

Of the scenarios that include logging (H1 – H4), net carbon sequestration is maximized in the baseline harvest scenario (H1) over the next 50 years. Sequestration steadily declines from the least intensive H1/F1 scenario to the most intensive H4/F2 scenario (H1/F1 = 195.3 Mg CO_2e ha^{-1} cumulative sequestration and 3.9 Mg CO_2e ha^{-1} year^{-1}; H4/F2 = 156.5 Mg CO_2e ha^{-1} cumulative sequestration and 3.1 Mg CO_2e ha^{-1} year^{-1}) (Table 3). This pattern is altered when fossil fuel displacement is considered. Net carbon sequestration increases as more fossil fuels are displaced by wood bioenergy. Therefore, when fossil fuel emissions are displaced by biomass energy emissions, high biomass feedstock scenarios (F2) result in greater net carbon sequestration as compared with the low biomass feedstock (F1) alternatives because there is a greater opportunity for fossil fuel substitution (Table 3, Figure 5). In both feedstock scenarios, however, less intensive harvests almost always result in greater net CO_2e sequestration. Although there is less woody biomass to displace fossil fuels, it is more carbon beneficial to harvest less and maximize carbon storage in the forest.

Over 100 years, similar patterns emerge. In all cases, high biomass feedstock scenarios (F2) sequester more net CO_2e than low biomass feedstock scenarios (F1) and greater fossil fuel displacement results in higher overall net CO_2e sequestration (Figure 5). All scenarios result in net positive carbon sequestration. By the end of the 100-year period, however, the annual rate of net CO_2e sequestration drops in some cases below zero, indicating that emissions are higher than sequestration (starting around year 60 for the intensively harvested H4/F1/0 and around year 85 for the baseline harvest regime H1/F2/0) (Figure 5). Although the rate of net forest ecosystem sequestration decreases slightly due to forest maturation, increases in harvest-related emissions are the primary driver of the reduction in net sequestration over time, specifically landfill forest product emissions (Figure 6). Methane from landfill forest products emits more CO_2e than all other harvested wood product sources, over 40 times the emissions from residue energy after 100 years in the BAU scenario (Figure 6). Forest ecosystem carbon emissions from forest floor detritus and soil decomposition far exceed emissions from all other forest product sources, but large amounts of forest growth counterbalance and surpass the impact of decomposition (Figure 6).

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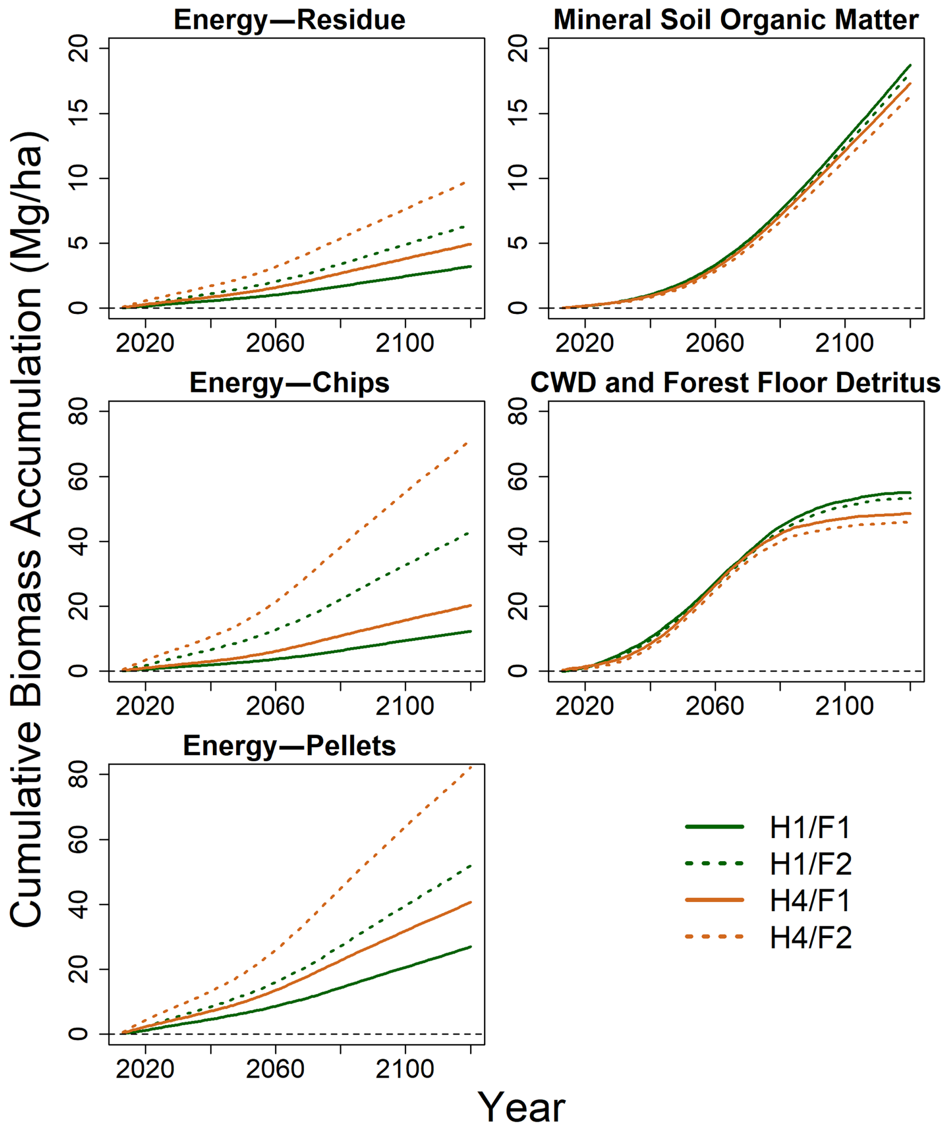

FIGURE 4 Biomass accumulation in coarse woody debris (CWD) and forest floor detritus, mineral soil, and three energy feedstock carbon pools—logging residues, chips, and pellets—after 100 years. The baseline harvest regime (H1) is being compared with the most intensive harvest regime (H4) across two feedstock scenarios. F1 diverts 25% and F2 diverts 50% of logging residues from the forest to energy feedstocks. Refer to Table 1 for scenario definitions.

The no harvest scenario sequesters more carbon than all other harvest/feedstock/fossil fuel displacement scenarios at 50 and 100 years, totaling 289.8 Mg CO_2e ha^{-1} (average 5.8 Mg CO_2e ha^{-1} $year^{-1}$) and 473.7 Mg CO_2e ha^{-1} (average 4.7 Mg CO_2e ha^{-1} $year^{-1}$), respectively (Table 3, Figure 5). Even though harvested wood products store carbon, the amount is far outweighed by the magnitude of carbon sequestered and stored in unharvested forests. Annually, there is between 44 times (H4/F1) and 79 times (H1/F2) more carbon sequestered and stored in forests versus harvested wood products, given the current distribution of harvested material to the different product pools. The average annual rate of carbon sequestration in live tree biomass is slightly lower in the no harvest scenario compared with the BAU scenarios. Foregoing timber harvest, however, is still significantly more carbon-positive when all sequestration and emissions variables are considered, including fossil fuel emissions displacement. Sequestration in harvested wood products is simply too low to outweigh the emissions associated with those pools.

DISCUSSION

Net carbon impact of variation in forest harvest regimes

Our results, which include forest ecosystem and harvested wood product dynamics, indicate that harvest intensification decreases net carbon sequestration. The BAU scenario

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TABLE 3 Cumulative net CO_2e sequestration (Mg C ha^{-1}) resulting from nine harvest (H) and feedstock (F) scenarios after 50 years.

	Displacement					
Scenario	**None**	**50%**	**60%**	**70%**	**80%**	**90%**
H0	289.8	289.8	289.8	289.8	289.8	289.8
H1/F1	195.3	209.3	212.1	214.9	217.7	220.5
H1/F2	194.5	227.2	233.7	240.2	246.7	253.3
H2/F1	186.7	202.7	205.9	209.1	212.3	215.5
H2/F2	185.5	223.1	230.6	238.1	245.6	253.2
H3/F1	168.4	187.5	191.4	195.2	199.0	202.8
H3/F2	166.9	212.5	221.6	230.7	239.8	248.9
H4/F1	158.6	181.1	185.6	190.1	194.6	199.1
H4/F2	156.5	211.0	221.9	232.8	243.7	254.6

Note: Descriptions of the harvest/feedstock scenarios are given in Table 1. The percentage of displacement refers to the amount of fossil fuel emissions that are displaced by wood biomass emissions.

results in an average annual net carbon sequestration of 3.91 Mg CO_2e ha^{-1} $year^{-1}$ for forests in the four northeastern states over the next 50 years and outperforms all other low feedstock scenarios (Table 3). This represents our best approximation of future sequestration based on current forest inventory, forest growth, and harvest levels. Intensifying the baseline harvest regime reduces net carbon sequestration in almost all harvest/feedstock scenarios relative to this baseline (Table 3), yet all scenarios result in net positive carbon outcomes over the next 50 years. An increase in harvest emissions (landfill decay, waste incineration, mill processing, and bioenergy production) resulting from intensified management drives the reduction in overall net carbon sequestration. While harvested wood product sequestration grows substantially, it is not enough to counterbalance the rise in harvest emissions, especially landfill methane emissions (Figure 5). Even though harvested wood product sequestration is 26% greater in the most intensive harvest regime (H4/F1) when compared with the baseline harvest regime (H1/F1), it only contributes about 2% of total sequestration. Contrary to studies that suggest more intensely managed forests reduce net CO_2e emissions (Kilpeläinen et al., 2016; Lundmark et al., 2014; Malmsheimer et al., 2008; Peckham et al., 2012), our results are consistent with other recent studies in the region and show that more intensive forest management regimes often result in worse carbon mitigation outcomes (Buchholz et al., 2017; Gunn & Buchholz, 2018; Mika & Keeton, 2015; Nunery & Keeton, 2010). Specifically, Mika and Keeton (2015) demonstrated that wood bioenergy harvests increase net CO_2 emissions relative to timber management that does not contribute to bioenergy, although both scenarios result in net positive sequestration. Shifting management toward structural retention practices and decreasing harvest frequency can significantly increase C sequestration (Nunery & Keeton, 2010).

Three critical components of our analyses interact and affect this conclusion: (1) the harvest regime and amount of forest biomass removal, (2) the degree to which bioenergy displaces fossil fuel use, and (3) the proportion of biomass diverted to energy feedstocks and wood products (Table 3, Figure 5). The intensity of harvest and amount of biomass removal determine whether carbon pools grow or diminish. The cumulative amount of carbon storage increases in all harvest scenarios (Figure 2), largely due to increases in forest biomass (live trees, forest floor detritus, and mineral soil organic matter), and may be sensitive to climate changes (Thom et al., 2019). Carbon stored in harvest pools (forest products and landfills) also increases, but to a much lesser degree (Figure 2). Although every harvest scenario predicts substantial increases in cumulative carbon storage across all carbon pools over time (Figure 2), intensified management reduces the magnitude of the increases (Figure 3). More intensively harvested landscapes in this region will equilibrate at lower average forest carbon stocks than less intensively managed landscapes (Brown et al., 2018). At the same time, harvested wood products and associated bioenergy emissions increase (Figures 2 and 3). Our results clearly indicate that reduced accumulation of forest carbon across the landscape from increased harvest outweighs additional forest product carbon storage (Nunery & Keeton, 2010) and the potential benefits of fossil fuel displacement over the next 50 years. The one exception occurs when we assume a very high (90%) efficiency of fossil fuel emissions displacement. In that case, the most intensive harvest regime/high feedstock scenario (H4/F2/90) sequesters slightly more net CO_2e (0.05 Mg CO_2e ha^{-1}) on average than the baseline harvest/high feedstock scenario (H1/F2/90). This suggests that the benefits of fossil fuel displacement can overshadow the reduction of forest ecosystem carbon in some cases, although the current harvest regime (H1/F2/90) accumulates more carbon than the intensive harvest regime (H4/F2/90) for nearly four decades. Because this result is driven primarily by fossil fuel displacement, it may be overly optimistic over longer time horizons. Fossil fuel displacement is expected to decline as fossil fuels use transitions to carbon-neutral energy sources (Liddle & Sadorsky, 2017), and renewable energy use is predicted to increase annually over the next several decades (EIA, 2022).

In scenarios that divert less biomass to energy production (F1 scenarios), more biomass is converted into wood products, and consequently, waste pools are larger.

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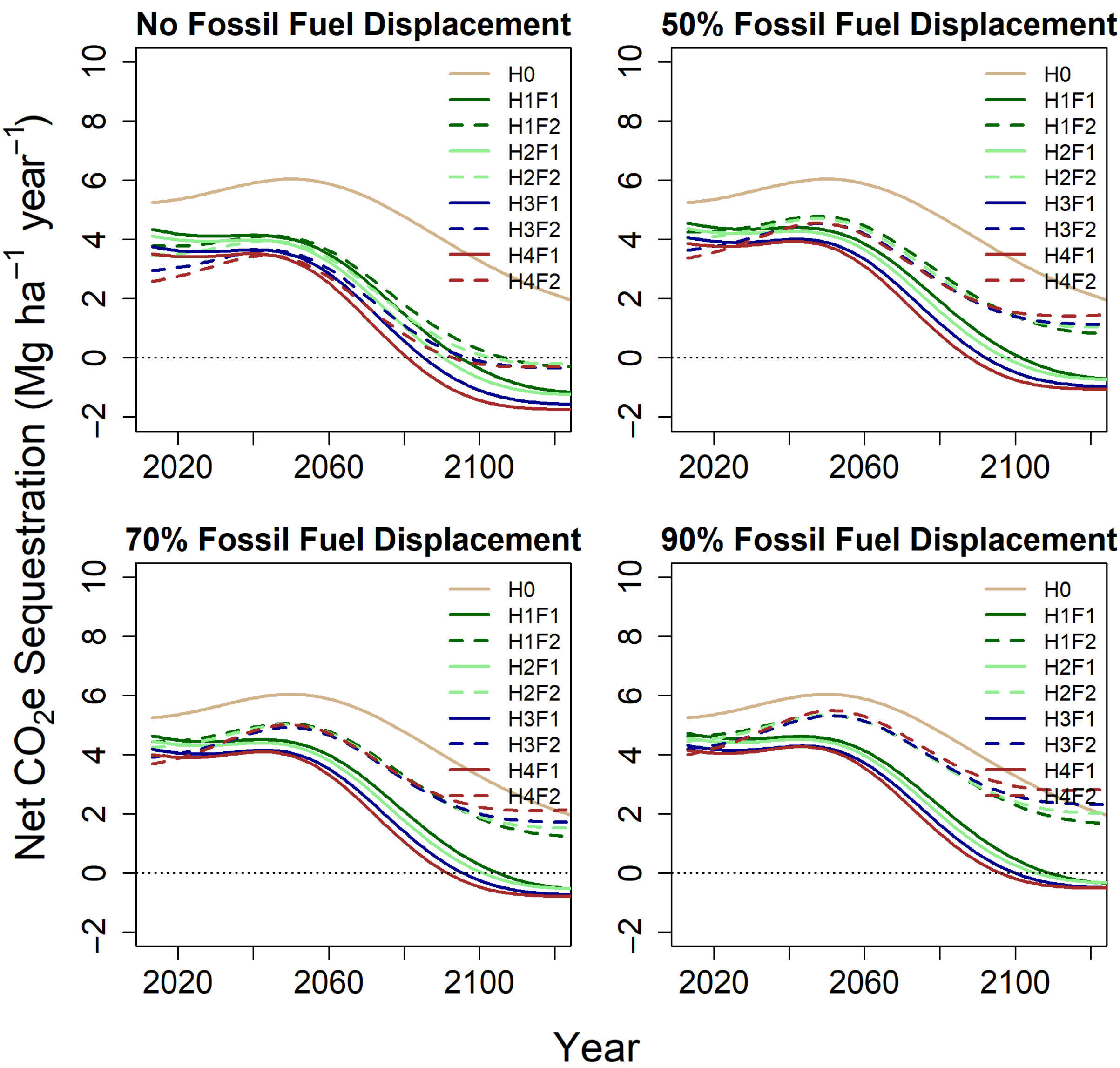

FIGURE 5 Net CO_2e sequestration resulting from nine harvest (H) and feedstock (F) scenarios over 100 years. The percentage of displacement refers to the amount of fossil fuel emissions that are displaced by wood biomass emissions. Refer to Table 1 for scenario definitions.

In these scenarios, annual emissions eventually surpass sequestration, and the annual rate of net sequestration goes below zero (Figure 5). That decrease in net sequestration over time is primarily due to a rise in emissions from harvested wood products, especially potent emissions of methane from landfills. Emissions surpass sequestration sooner in scenarios that divert more biomass to wood products and waste pools (F1 scenarios). For example, assuming 50% of fossil fuel emissions can be displaced by wood energy, the rate of sequestration shifts to negative after 64 years for the most intensive harvest scenario with low biomass energy diversion (H4/F1) and 78 years for the BAU scenario (H1/F1) (Figure 5). A second factor contributing to the decline in the overall rate of net sequestration is forest maturation. Our BAU harvest regime models estimate that the distribution of stand biomass across the landscape equilibrates after about 60 years when forest gross growth roughly equals natural mortality plus harvest removals.

Timeframe becomes particularly important when considering forest climate mitigation. The point in time when an alternative harvest regime cumulatively sequesters more carbon than the baseline is known as the carbon sequestration parity point (Jonker et al., 2014; Mitchell et al., 2012). In our analysis, the BAU scenario is the most favorable throughout the entire time period when compared with other low feedstock utilization scenarios (F1 scenarios). As harvest intensity and/or energy feedstocks increase, sequestration rates vary and the carbon sequestration parity point ranges from 12 years (BAU scenario with greater feedstocks) (H1/F2/50) to 40 years for the most intense harvest and

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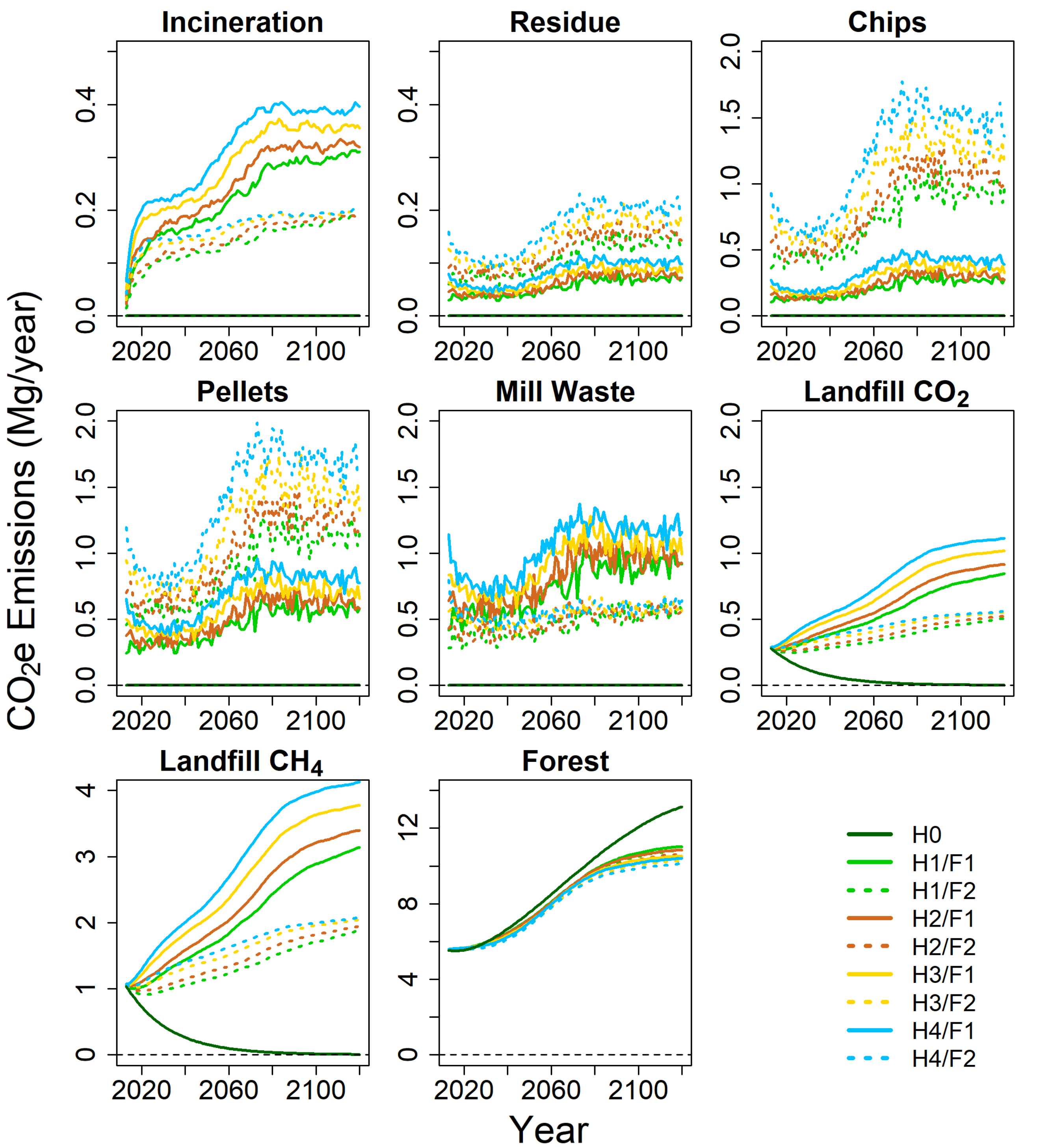

FIGURE 6 Annual emissions (CO_2e) from eight different sources resulting from harvest (H) and feedstock (F) scenarios over 100 years. Refer to Table 1 for scenario definitions.

feedstock scenario (H4/F2/50), respectively. This means that assuming 50% fossil fuel emissions displacement the BAU scenario outperforms the higher feedstock scenario H1/F2/50 until year 2032. Notably, the no harvest scenario (H0) sequesters more carbon than all harvest/feedstock/displacement scenarios for all timeframes (Table 3, Figure 5). We stress that the no harvest result is solely for comparative purposes and does not consider potential social and economic consequences of halting harvests across the study region and that demand for forest products would be displaced to other regions ("leakage"), potentially with far worse carbon consequences.

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Harvest effects on landscape forest carbon pools

The increase in cumulative carbon storage is largely due to the predicted increases in average forest biomass across the study area in all harvest scenarios. The current distribution of biomass in northeastern forests, which skews toward early and mid-successional biomass classes (Brown et al., 2018), still reflects intensive land use from the 19th and 20th centuries (Thompson et al., 2013). This, in addition to the partial harvest regimes characteristic of the Northeastern United States (Brown et al., 2018), allows for significant amounts of future projected carbon accumulation (Brown et al., 2018; Duveneck et al., 2017; Thompson et al., 2011; Wang et al., 2017).

A key feature of our model is the incorporation of the baseline harvest regime, calculated using FIA data, and the harvest effects on future forest composition, structure, and productivity. The resulting regional-scale predictions account for the small percentage of lands that are being harvested each year and the majority of the forested landscape that continues to accumulate biomass (Figure 2). This issue of scale is important. When a stand is logged to generate biomass energy, carbon is immediately released to the atmosphere through feedstock combustion, and more gradually through decomposition of logging residues, and then slowly removed from the atmosphere during forest regrowth. While this is true of an individual stand, it does not reflect the landscape-scale implications of harvest, forest growth, and biomass energy combustion. For the four northeastern states, roughly 3% of the non-reserved forestland is harvested in any given year, with a mean harvest intensity of approximately 30% of live biomass (Brown et al., 2018). The emissions that year that are due to those harvests are more than balanced in the same year by the net sequestration of the remaining 97% of the forestland that was not harvested that year.

Carbon implications of use of logging residue as a biomass energy feedstock

Despite the predicted increase in overall forest biomass, any removal of harvest residue from the forest will decrease the forest floor and mineral soil carbon pools (Canham, 2013). In contrast to several studies that suggest little or no carbon storage effects from residue feedstock utilization (Ranius et al., 2018), our analyses show a reduction in forest floor and mineral soil carbon pools as harvests intensify, greater amounts of feedstock are utilized for bioenergy, or both (Figure 3). While the annual reductions in forest floor and mineral soil carbon storage are small, doubling the amount of harvest residue removed from the forest and used as energy feedstock from 25% to 50% results in a 16.3-million metric ton C loss in forest detritus over 100 years (Figure 4). This is the equivalent of losing 0.1 metric tons of detrital carbon storage for every metric ton of biomass residue removed from the forest. Thus, there is a clear trade-off between increasing the amount of residue available for energy feedstocks and decreasing carbon storage across the landscape.

At question is whether the utilization of logging residues results in a carbon positive outcome overall. Using logging residues as an energy feedstock has garnered special attention due to an assumption that its use is inherently carbon neutral. That assumption is based on the premise that the emissions released while converting residues to bioenergy would have been released anyway through decomposition, thereby making the practice carbon neutral. However, intensifying harvests to generate additional logging residues for biomass energy production does not offset the reduction in detrital carbon pools and results in net negative carbon outcomes (Table 3, Figure 5). The carbon impact of utilizing greater amounts of logging residues for bioenergy within the BAU harvest regime is less obvious, however. Over a 100-year time period, 4.58 Mg C ha^{-1} of additional cumulative logging residues are available for energy production when comparing the baseline (BAU) harvest regime high (F2) and low (F1) feedstock scenarios. As more woody material is available to displace fossil fuel emissions and the displacement becomes more efficient, carbon benefits will increase (Table 3). Yet, solely increasing the use of residues as an energy feedstock yields an exceedingly small net carbon benefit (<1%) after 50 years, even when assuming maximum emissions displacement (Appendix S1). Furthermore, using additional residues for energy can only displace less than 1% of current fossil fuel consumption in NY, VT, NH, and ME (Appendix S1). We have focused here solely on the carbon consequences of removal and utilization of logging residues. In a broader context, those residues serve a wide array of ecological functions as a major input to detrital pools in northeastern forests (Aber et al., 1978). Harvest effects on stand structure characteristics, such as downed woody debris, have implications for habitat function and biodiversity as well as covarying landscape-scale carbon storage (Littlefield & Keeton, 2012; Schwenk et al., 2012; Thom & Keeton, 2019, 2020).

Forest biomass energy equivalent

Our results are fundamentally about trade-offs. Intensified harvests yield more wood products, but reduce storage in

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live biomass in forests. Removal of logging residue (tops and limbs) reduces carbon storage in detrital pools but can potentially provide limited displacement of fossil fuel emissions when used as a biomass energy feedstock. Net carbon sequestration is lower with intensified harvest but is affected by the magnitude of fossil fuel substitution. What is the potential energy return of all these trade-offs? We project that the BAU scenario will generate an average of 4.8 million metric tons of biomass energy feedstocks annually over the next 20 years in the four-state region. Roughly 2.2% of current levels of fossil fuel energy use could be displaced by these biomass energy feedstocks by our estimates, assuming a biomass energy conversion efficiency of 0.8, which is consistent with combined heat and power plants producing electricity and residential and commercial heat (Appendix S1).

Limitations

We do not directly address leakage in this study. Because energy feedstocks increase at the expense of traditional wood products (F2 scenarios), there is a possibility that sourcing the replacement wood products could be driven outside of the study area. In addition to global implications of leakage, the bioenergy market in the Northeastern United States is currently not the driver of shifts in use of harvested wood products. Biomass harvests are almost always a by-product of integrated operations that include other products like timber and pulp (Buchholz et al., 2019; Quinn et al., 2020). Although the volume is substantial, the price for biomass is noncompetitive with other products (Buchholz et al., 2019). Even so, studies show an appropriate leakage rate may be around 80% or even higher (Gan & McCarl, 2007; Pan et al., 2020; Wear & Murray, 2004), indicating that timber harvests could be reduced only slightly (< 20%) without triggering leakage. Based on the no harvest scenario (H0), we would expect a small reduction in harvest to yield higher net carbon sequestration than the BAU scenario, suggesting a role for forest conservation in climate mitigation policies (Gunn & Buchholz, 2018).

While many studies choose a specific fossil fuel alternative to bioenergy for GHG analyses, we opted for a more flexible approach. Our analysis presents a range of potential displacement factors regardless of specific energy conversion technologies or comparisons with particular energy alternatives. It is worth emphasizing, however, that as fossil fuel use declines and renewable energy production increases, wood will compare less favorably as an energy substitution. This transition to renewables can reduce net carbon benefits as the energy mix becomes more carbon neutral, and fossil fuel displacement becomes less relevant.

Conclusions

There is clearly a role for managed forests in mitigating GHG emissions (Fargione et al., 2018; Griscom et al., 2017; Shukla et al., 2019). The questions are to what degree and under what circumstances? Our analyses indicate that the BAU scenario in New York, Vermont, New Hampshire, and Maine sequesters more carbon over the next decade than any of the intensified harvest scenarios and increased feedstock utilization rates we examined. Modest reductions in harvest levels that do not trigger leakage would be expected to increase net carbon sequestration compared with current management. Our results suggest that any increase in the regional harvest regime will reduce net carbon sequestration in the landscape over climate policy-relevant time scales, even when more of the harvest is diverted to biomass energy production at very high assumed efficiency in displacing fossil fuel emissions. While all harvest/feedstock scenarios become more carbon competitive when fossil fuel emissions are displaced through wood energy, the transition to carbon-neutral energy sources may reduce the net carbon benefits of fossil fuel displacement over time.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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DATA AVAILABILITY STATEMENT

Novel code and data (Brown et al., 2023) are available from the Cary Institute of Ecosystem Studies via Figshare: https://doi.org/10.25390/caryinstitute.23096858.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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