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Tradeoffs and synergies of optimized management for maximizing carbon sequestration across complex landscapes and diverse ecosystem services

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ABSTRACT

Forest natural climate solutions such as improved forest management and reforestation have been identified as a cost-effective way to mitigate climate change. Several US states have GHG reduction policies, often citing forests as a key to meeting mitigation targets despite not knowing how specific practices impact carbon and other forest ecosystem services at the regional level. In response, we link a regional forest landscape model (LANDIS-II) with economic and policy data to assess how shifting forest management in Maine, USA, impacts the region's future carbon sequestration, timber supply, biodiversity, and landowner returns. Scenario analysis results show consistent tradeoffs between carbon sequestration and timber supply, with impacts diminished when managers shift to a land-sparing and balanced management approach consisting of permanent set-asides and intensive clearcut with planting regimes. We also estimate that carbon sequestration can increase by 15–25% over the reference case while still maintaining harvest levels by shifting to a broader mix of intensive and extensive practices. Further, we estimate that harvests could grow by 20% above the baseline and still positively affect forest carbon. In all cases, shifts in practices had a mixed impact on biodiversity due to the diverse habitat indicators evaluated for this study. Overall, we find that changes in forest management can lead to improved outcomes for both carbon and other forest ecosystem services of interest, provided managers are given the policy, economic, and social incentives to do so.

1. Introduction

Forests are a critical component of the global carbon cycle, sequestering and storing carbon in biomass (Fahey et al., 2010; Pan et al., 2011), and have great potential as a cost-effective natural climate solution (NCS) to mitigate climate change (Griscom et al., 2017; Austin et al., 2020). Forests also produce timber and store carbon, particularly when manufactured into durable harvested wood products (HWP) (Johnston and Radeloff, 2019; Zhang et al., 2020). While some studies have found that reducing harvests could increase carbon stocks (Erb et al., 2018; Skytt et al., 2021), this potential is limited by the societal demand for forest products as they also provide additional climate benefits when substituted for more greenhouse gas (GHG) intensive energy and materials such as fossil fuels and concrete (Roebroek et al., 2023) or by avoiding the potential leakage impacts that could result if forest management and harvest regimes change elsewhere (Pan et al., 2020).

Recent studies have emphasized the need to do more than reduce GHG emissions from fossil fuels if increasingly costly impacts are to be avoided (e.g., Riahi et al., 2017). To achieve climate goals, we must also look for ways to remove more carbon from the atmosphere and sequester it in biomass and HWPs. NCS such as planting trees, conducting timber stand improvements, and conserving or setting aside land that sequesters carbon or reduces GHG emissions can contribute to climate mitigation goals cost-effectively and enhance long-term ecosystem services. Within the United States, forests offset or remove the equivalent of about 13% of the country's GHG emissions (USEPA, 2023), and implementing NCS has the potential to mitigate an additional 10% or more of its net annual GHG emissions, with forestry contributing most of the mitigation potential (Fargione et al., 2018; Wade et al., 2022). However, the regional effects of forest management on carbon sequestration, fiber, and other forest ecosystem services are less known, particularly at the landscape-level.

Although US forests have consistently been a net annual carbon sink over the past few decades, there is no federal climate policy to incentivize additional GHG mitigation or carbon sequestration. In response,

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policymakers across the country have set state-level climate mitigation targets. In the state of Maine, the focus area of this study, policymakers have set a goal to reduce gross GHG emissions to 80% below 1990 levels by 2050 and to have Maine's net GHGs be 'net zero' by 2045. Several initiatives, including the Maine Climate Council (2020) and Maine Forest Carbon Task Force (2021), were established to evaluate the potential forest NCS opportunities to achieve these targets. Although the specific pathways and policies are still under development, a consistent recommendation is that Maine's forests should be a key source of mitigation, both in standing forests and HWPs. The Task Force and timber products industry is also focused on incentivizing forestry practices that increase carbon sequestration while also maintaining or enhancing Maine's annual harvest levels (FOR/ME, 2018). This situation in Maine aligns with current objectives and other uncertainties in other Northeast and Mid-Atlantic US states like New York, Vermont, and Maryland.

Maine's forests currently cover about 7.1 million hectares, nearly 89% of the state's land area. The forest industry sector is statewide and multi-faceted and has provided an average of more than $8 billion per year in economic impact over the past decade, while also supporting other important sectors of Maine's economy such as recreation and ecotourism (Bailey and Green, 2021; Bailey and Crawley, 2023). Maine's natural and working forest lands already sequester approximately 70% of current annual GHG emissions, and policymakers anticipate that its forests and wood products sector will continue to contribute significantly towards achieving the state's climate change mitigation goals. (Domke et al., 2023; Bai et al., 2020; Maine DEP, 2022). However, like many other heavily forested states in the US, Maine's forests and forest industry are expected to experience changes via continued shifts in market demand, distribution of land ownerships, policy adjustments, and climate change, which could have variable effects on the carbon sequestration and wood supply potential (Duveneck and Thompson, 2019; MacLean et al., 2021; Zhao et al., 2022). More research is needed to quantify the effectiveness of implementing various forest management practices across complex, multi-owner landscapes, particularly when landowners and other stakeholders have a range of objectives and perspectives on how the forest should be utilized.

While most of Maine's forests contribute to fiber production, many landowners have objectives for their lands beyond timber supply (Zhao et al., 2020). Results from the most recent National Woodland Owners Survey indicate that the three most common reasons for owning forestland given forest landowners nationally (Butler et al., 2021) and in Maine (USDA, 2021) and are: "to enjoy beauty or scenery," "to protect or improve wildlife habitat," and "to protect nature or biological diversity." It is not surprising that state and federal government initiatives targeting non-industrial forest landowners have increasingly focused on the sustainable production of forest ecosystem services (Kilgore et al., 2018). Similarly, investments in conservation initiatives to limit development on Maine's state and private land have also increased significantly over the past 30 years (Irland, 2018; Maine Land Trust Network (MLTN), 2017). As of 2021, >20% of Maine's land area was designated as conserved compared to about 5% in the 1980s (MEGIS, 2023). Despite the increased focus on maintaining working forests and ecosystem services more broadly, sustainability concerns are again being raised with the increasing interest in using forests as an NCS (Díaz et al., 2009; Littlefield and D'Amato, 2022). Of particular concern is the increased potential for converting mature and old-growth forests to young forests and the concurrent loss of ecosystem services in carbon-focused forestry (e.g., Moomaw et al., 2019). Important questions persist about the synergies and tradeoffs associated with managing forests to offset GHG emissions. We sought to analyze the potential impacts of varying timber market and land use constraints on Maine's forest stocks, carbon sequestration, and a suite of biodiversity indicators through 2100 under various management regimes.

Starting in the 1970s, Maine's government recognized the necessity for sustained timber yields and provided incentives for landowners to maintain their land as production forests, primarily through the introduction of the tree growth tax law that taxed working forests at their current use value. As a result, 4.4 million ha are currently enrolled in the program (MRS, 2022), with participants typically having a higher harvest intensity than non-enrollees (MFS, 2014). The 1989 Forest Practices Act (FPA) placed restrictions on clearcuts larger than 25 ha, thereby increasing partial cuts from about 50% of harvests in the state in the 1980s to nearly 95% today (MFS, 2022a). Concurrently, Maine's annual harvest area doubled after 1989, though the total harvest volume has remained somewhat constant (MFS, 2022c). As a result, the state's forests have a more extensive harvest footprint compared with the more intensive harvest regimes of the past (Legaard et al., 2015) yet variability in residual structure and composition remains high (Kuehne et al., 2019). Shifts in these forest management and harvest intensities influence both historical and future forest composition, standing inventory, carbon stock, and habitat conditions in the Northeast US, where Maine is located (Nunery and Keeton, 2010; Gunn and Buchholz, 2018; Thom and Keeton, 2020; MacLean et al., 2021; Dugan et al., 2021; Giffen et al., 2022; Patton et al., 2022). Although some of these challenges or issues are specific to Maine, the state is an interesting and important case study with significant implications for other forested states with diverse ownership patterns, mixed regulatory policy environments, and various climate action plans.

The primary goal of this study was to evaluate the impacts of varying trends in the utilization of diverse management practices on key landscape-scale ecosystem services, specifically carbon sequestration, timber supply, and biodiversity indicators in Maine's working forests. We used an integrated modeling approach that links a forest landscape model with economic and policy data and assumptions within an optimization framework to estimate the influence of implementing up to ten different silvicultural treatment options across 3.1 million ha of forestland in northern Maine from 2020 to 2100. We employed scenario analysis with the objective of maximizing forest carbon across the landscape while varying timber demand and land use constraints. Our ecological-economic framework provides both growth and yield and economic data for specific silvicultural regimes. This is an advancement over many forest sector models that simulate landscape-scale productivity changes under future conditions but ignore the role of specific management interventions (e.g., Daigneault et al., 2022) and forest ecological models that have detailed silvicultural systems but lack financial flows and other socio-economic indicators (e.g., MacLean et al., 2021).

This paper is organized as follows. First, we describe the study area, framework, and scenario design for our integrated forest sector model analysis. Next, we present the results of our analysis in Maine across different product and ownership classes. Third, we discuss our results in the context of how they can broadly inform the role of forest management in the context of natural climate solutions. We then conclude by synthesizing our findings for broader implications relevant to other areas and specific suggestions for future research.

2. Methods

We used an integrated modeling approach that linked estimates of aboveground live biomass from the widely used LANDIS-II (LANDscape DIsturbance and Succession) forest landscape model with economic and policy data and assumptions within an optimization framework known as the Maine Integrated Forest System Model (MIFSM) to quantify the potential impacts of alternative approaches to forest management across approximately 3.1 million hectares of forested area in northern Maine. The LANDIS-II model has been previously parameterized and calibrated for Maine's dominant tree species, including a detailed sensitivity analysis to identify influential parameters (Simons-Legaard et al., 2015) and benchmarking assessment (Simons-Legaard et al., 2021) using plot data from the US Forest Service Forest Inventory and Analysis Program (USFS FIA). For this study, we used MIFSM to conduct a scenario analysis evaluating the potential effects of managing the entire study area to maximize forest carbon sequestration 2020–2100 subject to realistic harvest supply requirements and harvest area constraints. The model was programmed to select the optimal area allocated to nine different forest management practices (Table 1), which included no harvest set-asides and a range of silvicultural systems and harvest intensities. Key outputs included 1) forest and harvested wood product carbon stock and sequestration, 2) timber harvest, 3) net timber revenue, and 4) change in forested area (ha) for five wildlife habitat and forest biodiversity indicators. Scenario estimates are compared to a baseline reference case based on historical patterns where timber is largely sourced from partial harvest and regular shelterwood management practices. Fig. 1 provides an overview of the integrated analysis, which is discussed in detail below.

2.1. Study area

Our northern Maine study area is comprised largely of primarily privately managed timberland that is predominantly held by "large landowners" (>4000 ha), representing a diverse range of ownership types (e.g., family, high net-worth individuals, timber investment management organizations, real estate investment trusts, and non-profit organizations), and managed commercially for wood products (Fig. 2). The forest is comprised of a mix of softwood and hardwood species of varying ages and grades, including balsam fir (*Abies balsamea*), white (*Picea glauca*), red (*P. rubens*), and black (*P. mariana*) spruce, white pine (*Pinus strobus*), white (*Betula papyrifera*) and yellow (*B. alleghaniensis*) birch, red (*Acer rubrum*) and sugar (*A. saccharum*) maple, and American beech (*Fagus grandifolia*). Tree advance regeneration in the study area is typically highly abundant with high species richness, large stem densities, and limited effects of herbivory (Bose et al., 2016).

2.2. Forest landscape model

LANDIS-II was designed to project the broad-scale effects of human and natural disturbances on forest dynamics (Gustafson et al., 2000; Mladenoff, 2004; Scheller et al., 2007). Within LANDIS-II, the forest is represented by a grid of interacting cells, aggregated by user-defined ecoregions representing areas of homogeneous environmental conditions. Forest succession processes, including tree establishment, growth, competition, and mortality are modeled based on empirically-derived data for each cohort (i.e., group of trees defined by species and age) in each cell. Emergent conditions (e.g., aboveground biomass) are tracked for each cohort. Execution of LANDIS-II requires information on tree species' life history attributes, specification of key ecological processes, and spatial representations of initial forest and landscape conditions. Each cell can contain multiple cohorts, and a combination of land cover or forest-type maps and forest inventory plot data generally provides initial forest conditions. The processes of seed dispersal, natural disturbance, and land use link cells.

The LANDIS-II model allows users to select different modules developed to simulate succession or a variety of disturbance agents. We used the latest version of the Biomass Succession module v. 5.3.1 (Scheller and Mladenoff, 2004) to model forest growth and succession

Table 1
Modeled forest management practices for 3.1 million ha Northern Maine study area. Annual average estimates based on individual LANDIS-II simulations for each of the 9 practices from 2020 to 2100.

Practice	Description	2020–2100 Annual Average*			
		Harvest/ Treated Area (ha/yr)	Harvest Rate (tC/ha/yr)	Net Harvest Revenue ($/ha/yr)	Forest Carbon Sequestration (tC/ha/yr)
Partial harvest	A moderate harvest option targeting 50% removal of stand biomass but with no explicit stand regeneration objectives. Removals weighted towards cohorts >60 years old. Prescribed reentry and removal of eligible cohorts every 50 years.	63,789	0.75	$23	0.93
Extended Rotation	A moderate harvest option targeting 50% removal of stand biomass but with no explicit stand regeneration objectives. Removals weighted towards cohorts >100 years old. No prescribed reentry, but all stands eligible for selection after 50 years.	56,404	0.62	$20	1.16
Clearcut with Natural Regeneration	Initial removal of 100% of live biomass for cohorts >5 years old. Regeneration relies completely on growth of existing seedling cohorts or establishment of new cohorts from seed. No additional site preparation or removal of competing or undesirable species was modeled. The resulting even-aged stand was expected to be ready for harvest at year 50.	48,952	1.11	$36	0.74
Clearcut and Plant	Initial removal of 100% of live biomass for cohorts over 5 years old. Regeneration relies on planting. No additional site preparation or pre-commercial removal of competing or undesirable species was modeled. Commercial thinning (CT) was conducted at year 25. The resulting even-aged stand was expected to be ready for harvest at year 50.	83,678	1.17	$32	0.70
Commercial Thin & Clearcut and Plant	Initial commercial thin (CT) with 35% removal of live biomass, followed by clearcut and plant at year 20. Commercial thin at year 50 and overstory removal at year 80.	95,755	1.07	$36	0.37
Regular Shelterwood	Initial establishment cut removed 60% of live biomass, followed at year 10 by removal of remaining overstory. Pre-commercial thinning at year 25. Commercial thinning at year 40. Apply next cycle establishment cut at year 60.	88,577	0.97	$29	0.76
Continuous Cover	Commercial thin (from below) at 30-year intervals with 35% removal. Results in multi-aged stands continuously harvested every 30 years.	102,335	0.79	$16	0.86
Irregular Gap	Removals were a combination of small gaps (with 100% removal) within a forest matrix thinned on a 20-year cycle. Gaps were also thinned on a 20-year cycle after creation. Results in multi-age stands continuously harvested every 20 years.	112,240	0.71	$19	1.01
No Harvest Set Aside	Forests are not managed or harvested at all over the 100-year simulation period. This is the equivalent of a forest 'set aside' or 'permanent conservation'.	0	0.00	$0	2.18

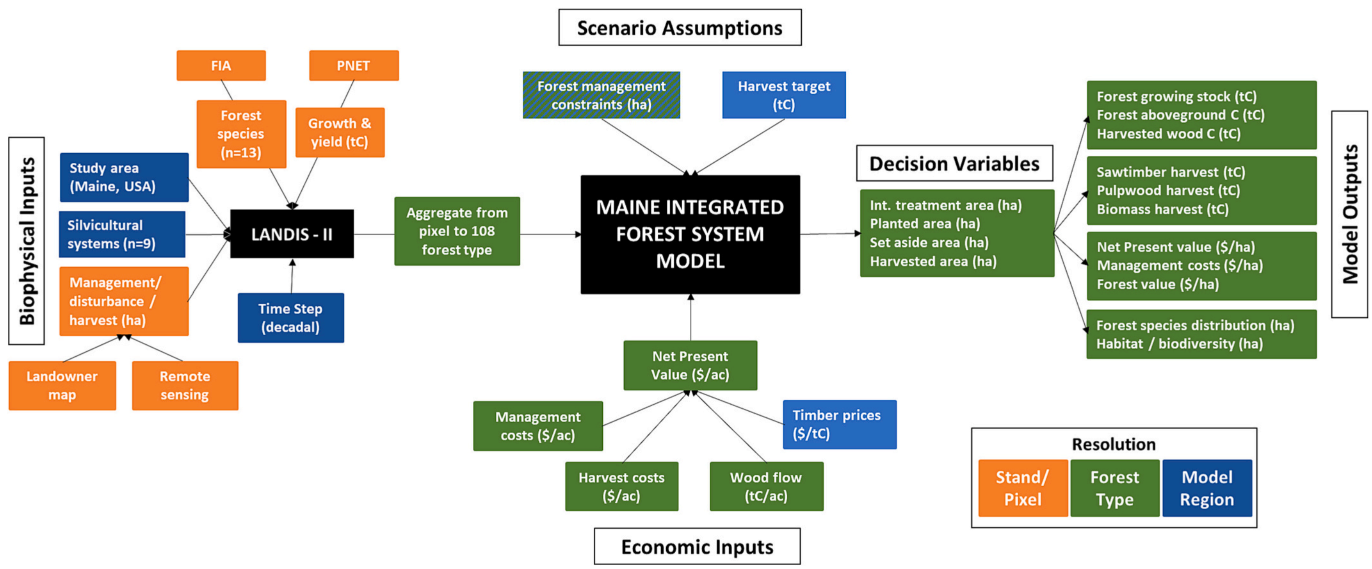

Fig. 1. Maine Integrated Forest System Model (MIFSM) framework that combines the forest-landscape model (LANDIS-II) with economic and policy scenario assumptions within an optimization framework.

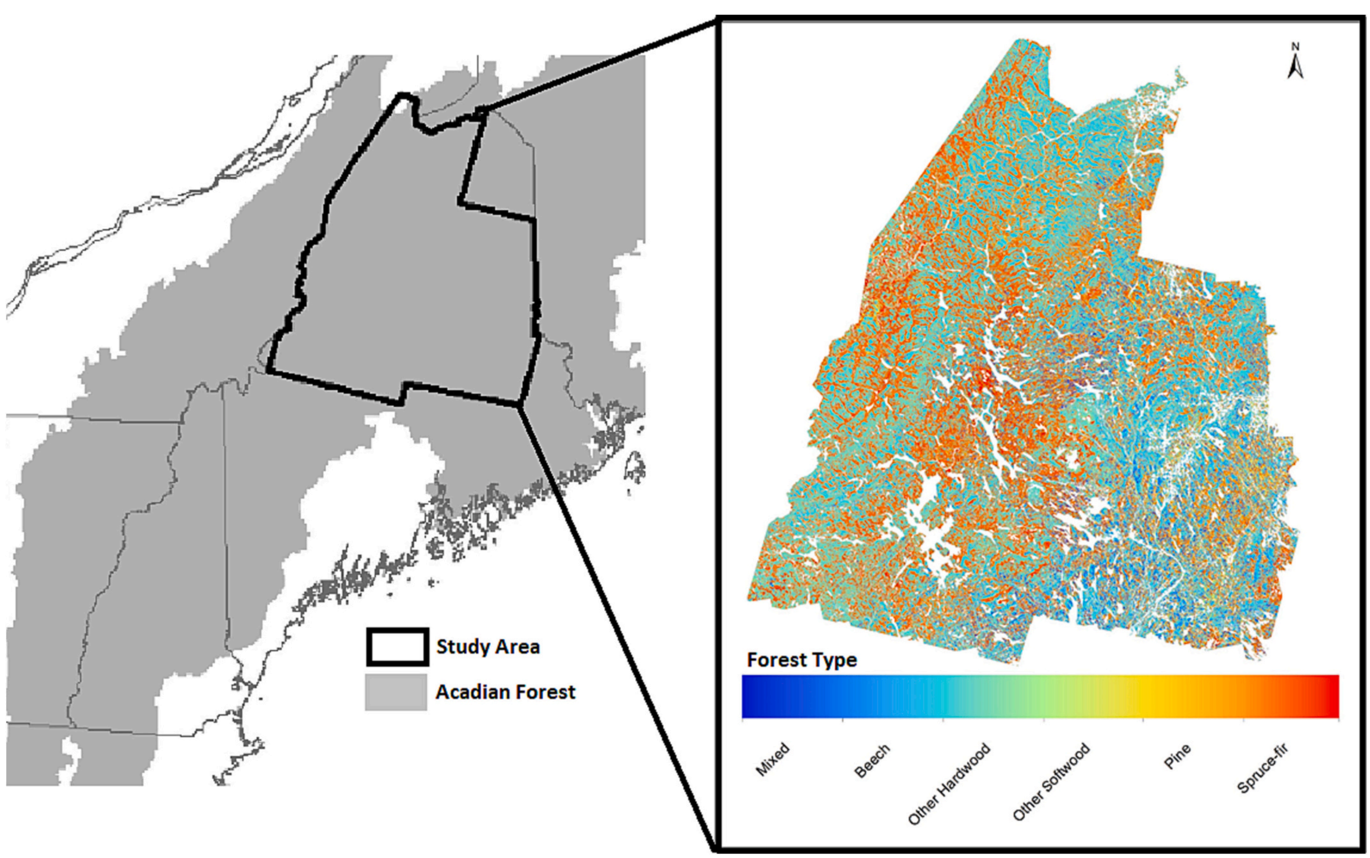

Fig. 2. Northern Maine forest study area (3.1 million ha) and initial forest type classification.

and to estimate changes in live, aboveground biomass. This module was the focus of a global sensitivity analysis to identify influential parameters (Simons-Legaard et al., 2015), which informed a subsequent study by Simons-Legaard et al. (2021) that evaluated the effects of business-as-usual harvesting on Maine's 13 most abundant tree species under the contemporary climate based on 30-year normal PRISM climate data. Initial conditions were derived from maps of tree species relative abundance ca. 2010 and disturbance history, which were developed using USFS FIA plot data and Landsat satellite imagery following the methods of Legaard et al. (2020). Forested cells were populated with cohort information (i.e. dominant species and approximate age) at a spatial resolution of 30 m; initial estimates of total live aboveground biomass and relative species abundances were calibrated to match USFS FIA plot data. See Simons-Legaard et al. (2021) for additional details about species parameterization and biomass calibration. We used the Simons-Legaard et al. (2021) map of cohorts for initialization and calibrated set of species-specific parameters in our simulations (Table S1).

We used the HARVEST module 4.4 (Gustafson et al., 2000) to model the spatiotemporal effects of nine forest management practices (Table 1) on live, aboveground biomass and harvest dynamics across our study area between 2010 and 2110. Practices varied in the timing of entries, biomass removal rates, regeneration strategy, and forest type application, but each practice (except no harvest set aside) was calibrated to achieve an even flow of total biomass removal at a 10-year time step to the maximum extent possible. The total biomass removal target of approx. 2.1 million tons of carbon (~7 million green tons of biomass) per year, was calculated using USFS FIA plot data from our study area. At the beginning of each simulation, all forested cells, except for those in the approximately 147,000 ha of reserved public lands (e.g., Baxter State Park), were treated as eligible for harvest. Because practices varied in their stand-level target rates for biomass removal, from 35% (e.g., Continuous Cover) to 100% (e.g., Clearcut), as well as the number and timing of entries (Table S2) average harvest area required to meet the total biomass target also varied between practices (Table 1). Each of the 9 practices was simulated separately to provide the species, age, and biomass information needed for optimization (See Section 2.3). We did not incorporate the potential effects of climate change in our simulations. Although previous research suggests that climate changes in the northeastern US will gradually affect tree species productivity and regeneration, land use has consistently been identified as the primary regional driver of forest dynamics over this century (Wang et al., 2018; Duveneck and Thompson, 2019; MacLean et al., 2021).

Over the course of a simulation, LANDIS-II tracks aboveground biomass for each cohort in each cell and can provide output maps at a user-specified interval that summarize live aboveground biomass, by species and cohort age range, and total harvested biomass. We used the Biomass-by-Age Output extension to produce aboveground estimates by species and for two age cohorts (i.e., less than or >40 years old for coniferous species and 50 for deciduous species) at the end of each 10-year harvest interval (e.g., 2010–2020, 2020–2030, etc.). Because LANDIS-II does not explicitly model tree diameter or height, we used the biomass-by-age maps to disaggregate growing stock into biomass/pulp and sawlog categories using the assumption that any coniferous species cohort >40 years of age (or 50 for deciduous species) would be sawlog in size, while coniferous species cohorts <40 (or 50 for deciduous species) would be biomass/pulp.

We used a similar approach for the harvest data, comparing aboveground conditions before and after in harvested cells to assign total removed C to species and age cohorts based on percent change. Estimates using this age-based assumption aligned closely with harvest levels reported by the Maine Forest Service (2022c). Carbon stored in harvested wood products (HWP) was estimated following the WPsCS Estimator in Wei et al. (2023), which used Maine-specific parameters to convert saw, pulp, and biomass harvests to carbon flows and storage in a range of wood products and landfills over time. Total forest carbon stock was assumed to be the sum of AG and HWP C. The total forest carbon sequestration was quantified as the annual change in the total forest stock.

In addition to regional C and timber outcomes, we calculated and compared area outcomes between practices for various wildlife habitat and biodiversity indicators. We chose indicators representing the range and diversity of forest developmental stages (early-, mid-, or late-successional) and regionally important forest types (northern hardwood or spruce-fir forest). These indicators also capture the inherent tradeoff associated with maximizing sequestration rates by creating young forests versus maximizing carbon storage in older forests.

Late-succession (LS) forests in the northeastern U.S. are structurally complex forests characterized by a high density of large-diameter trees, snags, and downed logs that host many unique species of plants and animals (Whitman and Hagan, 2007). <2% of Maine's forest is estimated to be LS. Our study adopted the commonly used regional definition of LS forest as >100 years old and calculated decadal change in LS forest area with >75% relative abundance of northern hardwood species (sugar maple, yellow birch, and American beech) or spruce-fir species (balsam fir and spruce sp.).

As our indicator of mid-successional (MS) forest habitat, we calculated change in American marten (*Martes americana*) habitat. Marten are a medium-sized member of the weasel family that in the northeastern U.S. occupy areas of mature (i.e., mid-to-late successional) forest with a high basal area (>18 m^2 ha^{-1}) and tall (>9 m) trees (Payer and Harrison, 2003). We used forest age as a proxy for height, assuming a threshold age of 40 years old, and developed a simple linear regression equation from FIA data to calculate the biomass threshold corresponding to 18 m^2 ha^{-1} (i.e., 5855 g m^{-2}).

Early-successional (ES) habitats have declined in New England following past afforestation and recent increases in forest conversion (Brooks, 2003; Litvaitis, 2003).Timber harvesting can create ES habitats by removing mature trees and restarting the successional process, which research in Maine suggests can be particularly beneficial to "disturbance-dependent" songbirds that use shrub (e.g., Mourning Warbler (*Geothlypis philadelphia*), Palm Warbler (*Setophaga palmarum*), and Alder Flycatcher (*Empidonax alnorum*)) or sapling (e.g., Common Yellowthroat (*Geothlypis trichas*), Chestnut-sided Warbler (*Setophaga pensylvanica*), and Nashville Warbler (*Leiothlypis ruficapilla)* habitats (Hagan et al., 1997; Hunter et al., 2001). Similar to our marten habitat indicator, we defined ES shrub/sapling bird habitat using a structure-based threshold (≤ 13.5 m^2 ha^{-1}; Hagan and Meehan, 2002).

Finally, snowshoe hare (*Lepus americanus*) is considered a keystone species in northern boreal forests and an important prey species throughout its range for many carnivores, including the U.S. federally threatened Canada lynx (*Lynx canadensis*). Lynx are specialist predators of hares, and because hare density can act as a regulating factor on lynx populations, the presence of high-quality snowshoe hare habitat is considered essential for lynx conservation in the U.S. (U.S. Department of Interior, 2008). Based on previous research in Maine, we identified high-quality hare habitats as forests between 10 and 40 years old, with spruce-fir relative abundance >50% (Simons-Legaard et al., 2013).

2.3. Forest system optimization modeling

For this study, MIFSM was programmed to evaluate 108 unique forest-type (*f*) combinations (aggregated from LANDIS-II 30 m output maps) that varied in species, site productivity, and initial stand conditions to find the optimal mix of management practices (*m*) and harvest schedules to implement across all 3.1 million ha (*X*) of the landscape over time (*t*) to meet a specified objective, subject to ecological, economic, and forest policy constraints. As this study was largely interested in the potential for Maine's forests to be an effective NCS and sequester carbon, we defined the objective function as:

$$Max\ C = \sum\nolimits_{f,m,t} \{AGC_{f,m,t} + \mathrm{HWPC}_{f,m,t}\} * X_{f,m,t} \quad (1)$$

where AGC is the aboveground carbon stock (or sequestration) estimated by LANDIS-II for the 9 forest management practices (Table 1) for a given decade t = 2020–2100, and HWPC is the harvested wood product carbon estimated using the WPsCS Estimator. Summing the total carbon across all forest types and management options yields the total forest carbon accrued across the study landscape.

Although the primary objective in this study was to maximize forest carbon, most commercial forest landowners and managers want to profit from managing and selling timber. Here, net timber revenue (π) is earned from the production and sale of sawlogs, pulp, and biomass less the input costs to regenerate and manage the forest and harvest and haul the logs to the mill:

$$\pi = \sum\nolimits_{f,m,t} \left\{ (P)\ Q_{f,m,t} - \omega^{vc}_{f,m,t} - \omega^{fc}_{f,m,t} \right\} * X_{f,m,t} \quad (2)$$

where P is the product output price (saw, pulp, biomass), Q is the product output quantity, and ω^{vc}, ω^{fc} are the respective variable and fixed input costs.

MIFSM can also track changes in area suitable for the five biodiversity indicators (β) described in Section 2.2. Per hectare values are specified via the parameter $\gamma_{f,m,t}^{biodiv}$, which were estimated from LANDIS-II species and age output maps. These indicators were allowed to vary by silvicultural treatment, forest type, and time. Summing over the area of silvicultural treatment yields the total area of each biodiversity indicator across the Northern Maine study area:

$$\beta = \sum\nolimits_{f,m,t} \gamma_{f,m,t}^{biodiv} * X_{f,m,t} \tag{3}$$

Forest managers can also be limited in the extent of management practices they can implement due to capital, site productivity, policy, and social license to operate constraints, and thus varied by scenario to represent the potential level of stringency (see Section 2.4). For some scenarios, we specified upper bound values to limit the amount of land that can be allocated to no harvest set-aside, clearcut, and planted treatments, as environmental and economic policy concerns are often raised by both forest managers and the public when the idea of expanding these treatments is discussed, noting a desire to strike a balance of working forests, intensive silviculture, and forest conservation (Maine Climate Council, 2020; Irland, 2020; Meyer et al., 2014).

The business-as-usual reference (BAU-reference) scenario fixed the allocation of management areas to follow the distribution of practices carried out over the past 20 years through 2100. The model also assumed a fixed land area constraint such that total land area must remain constant for each forest combo type f, although area treatment m can vary. We also included a non-negativity constraint such that the area allocated to each silvicultural treatment must be greater than or equal to zero.

Timber price data for the model was sourced from MFS (2022b) and Stevens (2018). Regeneration, intermediate treatment, logging, and hauling cost data were obtained from Kenefic et al. (2014), Hiesl et al. (2015), Hiesl et al. (2017), Koirala et al. (2017), Germain et al. (2019), Daigneault et al. (2021), and Walker et al. (2023). Data from sources with multiple observations were averaged over the five most recent years. All prices and costs were adjusted to 2022 real prices using the US producer price index.

MIFSM was programmed in GAMS as a linear optimization problem and solved using the MINOS solver. The model was solved decadal for 2020 to 2100 and produces estimates in both decadal and annualized mean averages over the 80-year period. Key model parameters are summarized at the aggregate forest type level in Table S3. The analysis conducted in this paper focused on the effect of different harvest targets and management constraints on forest carbon, timber, and biodiversity indicators (Table 2). Additional scenario and sensitivity analysis using the MIFSM framework can be found in Daigneault et al. (2021) and Walker et al. (2023).

2.4. Scenario analysis

We took a scenario analysis approach to evaluate how the distribution of forest practices could vary under a range of management areas and annual harvest target constraints. In most scenarios, the objective was to find the optimal distribution of forest management practices across the entire study area landscape to maximize total carbon (ecosystem and harvested wood product) subject to the specific constraints. Estimates from our max carbon sequestration scenarios were compared to the historical BAU-reference scenario. Harvest targets for each subset of scenarios ranged from 1.6 to 2.6 million tons of carbon per year (MtC yr^{-1}), or very low (VL) to very high (VH) harvest levels. The medium to high-level targets fall within historical harvest figures and processing capacity, while the low targets have not been realized in several decades (MFS, 2022c). Silvicultural treatment area constraints were set for some scenarios with upper bounds imposed on no harvest set-asides and clearcuts to represent historical (Current) and potential future (Relaxed, None) policy limitations for expanding these management options.

1. Business-as-usual reference (*BAU – Reference*): Continue to follow historical trends in silvicultural treatment areas and annual harvests.
2. Max carbon with current area constraints and harvest target: (*Max C – Current Area Cons – Harv Target*): Maximize total forest carbon sequestration across landscape under varying harvest targets with historical clearcut and set aside area upper bound constraint.
3. Max carbon with relaxed area constraints and harvest target: (*Max C – Relaxed Area Cons – Harv Target*): Maximize total forest carbon sequestration across landscape under varying harvest targets with twice the historical clearcut and set aside area upper bound constraint.
4. Max carbon with no area constraints and harvest target: (*Max C – No Area Cons – Harv Target*): Maximize total forest carbon sequestration across the landscape under varying harvest targets. With no treatment area upper bound constraint.

A total of 19 scenarios were run in MIFSM to evaluate the potential effects of managing the study area to maximize annual forest carbon sequestration (aboveground + harvested wood) from 2020 to 2100, subject to exogenously specified1) silvicultural treatment area and 2) harvest target constraints. The model selected the optimal area of each treatment option, by forest type, to implement over the entire time frame. Key metrics evaluated included management area, timber harvest, forest carbon stocks and sequestration, net revenue, and habitat area for our five biodiversity indicators (LS spruce-fir, LS northern hardwoods, lynx, marten, and ES bird).

3. Results

The overall results of our scenario analysis show a clear and

Table 2
Northern Maine forest management study objectives and constraints by scenario group.

Scenario Group	Model objective	Harvest target (tC/yr)*	No harvest set aside area constraints (ha)	Total clearcut area upper bound (ha)	Clearcut and plant area upper bound (ha)
BAU – Reference^	Fix management to specified area	2,150,000	562,900	367,200	100,000
Max C – Current Area Cons – Harv Target	Max Total C Sequestration	1,600,000–2,600,000	562,900	367,200	100,000
Max C – Relaxed Area Cons – Harv Target	Max Total C Sequestration	1,600,000–2,600,000	1,125,700	734,400	200,000
Max C – No Area Cons – Harv Target	Max Total C Sequestration	1,600,000–2,600,000	n/a	n/a	n/a

^ Follows historical harvest and silvicultural treatment area; management also includes partial harvest and regular shelterwood.
* Harvest targets: Very Low (VL) = 1.6 MtC/yr, Low (L) = 1.8 MtC/yr, Med-Low (ML) = 2.0 MtC/yr, Med-High (MH) = 2.2 MtC/yr, High (H) = 2.4 MtC/yr, Very High (VH) = 2.6 MtC/yr.

consistent tradeoff between increasing forest carbon sequestration and timber supply. This tradeoff is diminished when Maine's forests can shift management towards a more land-sparing approach where most of the study area consists of either no harvest set-asides or an intensive clearcut and planting regime. We also found that moving the distribution of forest management away from the historical reference case where timber is largely sourced from partial harvest and regular shelterwood management to a broader set of practices can increase both carbon stocks and timber supply relative to the status quo, although there is a mixed effect on biodiversity.

3.1. Initial conditions

The initial (2020) conditions of our model analysis estimated that the 3.1 Mha of our study area was forest. This resulted in an initial aboveground carbon stock of 130.7 MtC that sequestered C at a rate of 0.75 MtC yr^{-1}. >2.1 MtC yr^{-1} was harvested in the initial period, accruing landowners $90 million in net revenue. About 60% of the removals were pulp and biomass, with the remainder classified as sawlogs. Collectively, these harvested wood products sequestered and stored nearly 0.47 MtC yr^{-1}, which resulted in a total forest carbon sequestration rate of 1.2 MtC yr^{-1}. In terms of biodiversity indicators for wildlife habitat, 52% of the study's initial study area was suitable for marten, followed by lynx (16%), early-successional bird (9%), late-successional hardwoods (0.3%), and late-successional spruce-fir (0.2%). All of these estimates closely match the data used as model inputs, by design of the calibration methodology.

3.2. Silvicultural treatment area

The model estimated that both the harvest target (1.6–2.6 MtC yr-1) and clearcut and set-aside area constraints (Current, Relaxed, None) have a noticeable effect on the distribution of management practices that could be implemented across the 3.1 million ha study area (Fig. 3). The treatment area distribution for all alternative scenarios were different to the BAU-reference case, where management largely consisted of partial harvest and regular shelterwood. When limits were imposed on clearcut and set aside areas to match recent trends, the irregular gap and extended rotation practices were the dominant practices selected for the low (L) harvest targets, while most land shifted to regular shelterwood for medium-high (MH) to very high (VH) harvests. In this case, the historical permanent set aside area could be maintained for all except the VH harvest target, in which about 75,000 ha (−13%) of the area initially designated as 'no harvest' would have to be brought into production to meet timber demand. Less intensive harvest practices such as partial harvest and extended rotation, along with the highly-intensive irregular gap treatment, make up a large proportion of the forest area for the very low (VL) to medium-low (ML) harvest targets, as they have a relatively high carbon sequestration but lower harvest removal rates per entry.

When treatment area constraints were relaxed such that clearcuts and no harvest set-asides could expand to double the historical rate (i.e., relaxed area limit in Fig. 3), the clearcut treatments increased to the upper bound of allowable area in all cases, while the no harvest option upper bound area would be met for the VL to ML harvest targets. When harvest targets were increased to the MH to VH range, the regular shelterwood area expanded at an average rate of 1.2 ha per tC of timber harvested. In contrast, when harvest targets were reduced to the L and VL range, the area allocated to extended rotation and irregular gap harvests increased but to a lesser degree than under the current area limit scenarios, as it is more efficient to devote more land to a mix of no harvest set-asides and clearcuts.

Treatment areas under the no area limit scenarios clearly indicate that if forest managers did not face any land use policy constraints, dividing the landscape into intensive clearcutting and planting and no harvest set-asides would be the most efficient way to maximize carbon sequestration while still meeting the harvest targets. For the VL harvest scenario, timber targets could be achieved with 1.34 million ha (43%) of forestland devoted to timber production, while the remaining area could be set aside. As the harvest target increased, the area that must be devoted to clearcutting increased at an average rate of 0.84 ha tC^{-1}, such that only 29% (0.89 million ha) of the landscape is allocated to no

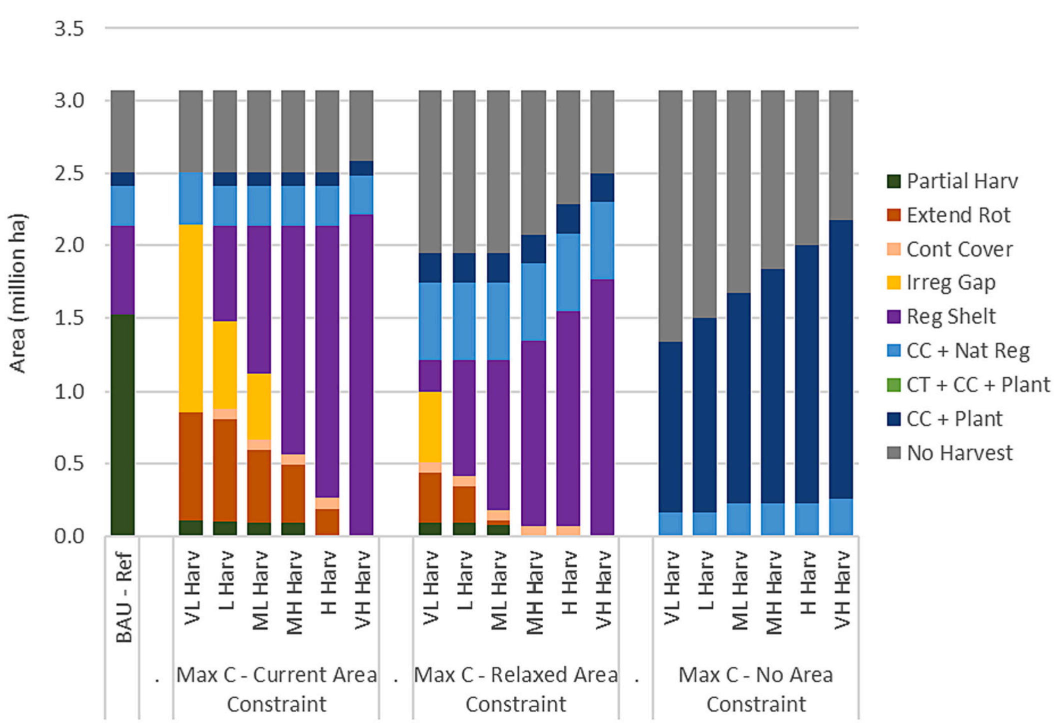

Fig. 3. Optimal distribution of silvicultural treatment area by modeled scenario. VL = very low, L = low, ML = medium-low, MH = medium-high, H = high, VH = very high.

harvest set-aside in the VH scenario. However, even in this case, the no-harvest area is 58% (0.33 million ha) greater than the BAU scenario.

3.3. Forest carbon and timber impacts

Forest carbon stock and sequestration varied across both treatment area constraints and harvest targets, with lower harvests and less stringent constraints contributing to more forest carbon (Fig. 4, Fig. S1). For all scenarios, total (AG + HWP) forest C stocks were estimated to increase over the course of the century, from about 133 MMTC in 2020 to an average of 229 MMTC in 2100. This results in our study area continuing to sequester carbon over the next 80 years at a rate of about 1.1 MMTC yr^{-1} across all scenarios. In nearly all scenarios, carbon stocks increased at a declining rate, but sequestration only became negative when VL and L harvest targets were combined with current area limits, and only then at the end of the century.

In many scenarios, shifting the distribution of management practices away from the BAU-Reference case resulted in more forest carbon, particularly in the second half of the century after the full transition to other practices becomes more established. As a result, mean carbon sequestration could increase by 16%, 22%, and 29%, respectively, for the current, relaxed, and no-area limit scenarios.

Over the 2020–2100 period, an average of about 60% of the annual total forest carbon sequestration was estimated to occur in AGC, with 40% being sequestered in HWPs. For the VL harvest targets, the AGC contribution increased to nearly 75% of the total, whereas it decreased to 45% for the VH target scenarios. Coupled with the fact that overall carbon stocks are greater under the low harvest scenarios, these results highlight that while HWP C can be an important contributor to the forest sector as an NCS, there is potentially more value for sequestering carbon as AGC than HWP C.

Harvest removals for any given scenario were relatively consistent over time, which was by design given that each scenario had a mean harvest target to meet as part of the optimization. Within each scenario, however, harvests can fluctuate on a decadal basis, which is to be expected given the uneven age distribution of Maine's forests and that the model considers how forests take time to transition when new management practices are being implemented across the landscape. As a result, decadal harvest area could fluctuate by as much as 25% from one period to the next even though the mean timber flow is constant for any given scenario. Finally, the pattern of the alternative scenario harvest trajectories also varied from the reference case, which experienced the

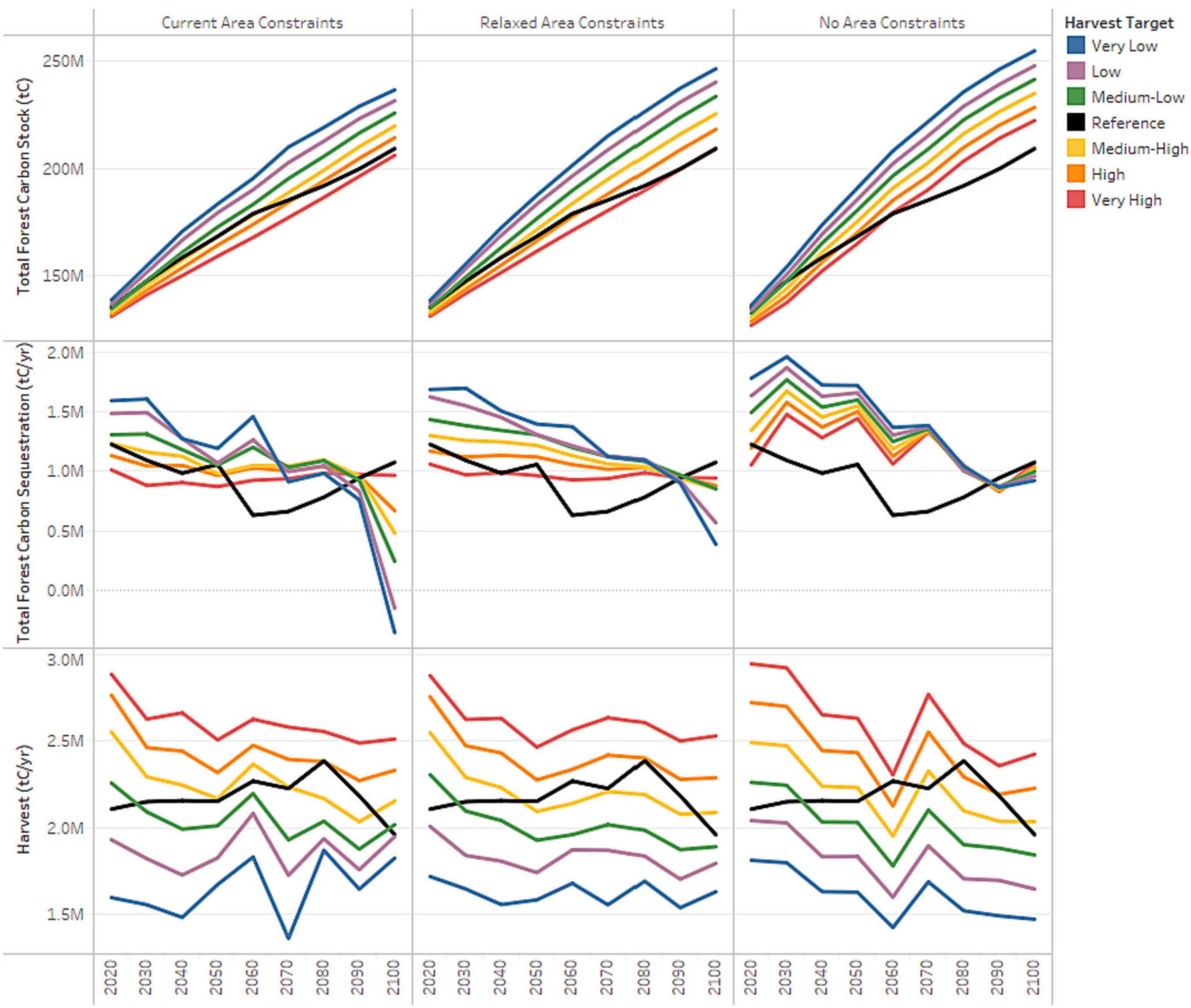

Fig. 4. Forest total carbon stock (tC), carbon sequestration (tC/yr) and harvest (tC/yr) under alternative harvest targets and practice constraints, 2020–2100.

largest decline in harvest over the last 20 years of the simulation due to the uneven distribution of area and biomass available for the partial harvest treatment.

Plotting mean total carbon sequestration and harvest rate estimates by forest type provided insight into how the two metrics are correlated, but can vary across silvicultural treatment, and explained why certain treatments are more prevalent under different scenarios (Fig. 5). First, the harvest rate (tC/ha/yr) and sequestration rate (tC/ha/yr) had a strong negative relationship. Second, forests treated by clearcut (with natural regeneration or planted) were clustered at the top of the plot, highlighting their potential to yield higher harvest output while maintaining positive carbon balance at a higher rate than many other treatments. Planting outperformed natural regeneration because artificial regeneration stimulates faster growth and yield, resulting in more carbon in standing biomass while still allowing intensive harvests to occur across the landscape simultaneously. Third, less intensive treatments such as extended rotation and continuous cover tended to have higher sequestration rates, but lower harvest rates, highlighting their limited potential to contribute to the higher harvest target scenarios. Finally, these rates can vary across the same forest type combination, which can be seen by the size of potential area that a practice can be undertaken in, highlighting the potential for some forest types within a given treatment to be more advantageous than others to meet specific objectives.

3.4. Biodiversity indicator impacts

The alternative timber demand and land use constraint scenarios resulted in varied impacts to the habitat areas of our five biodiversity indicators (Fig. 6). Compared to the reference scenario, changes in management to maximize C sequestration resulted in more co-benefits for early-successional habitats than mid- or late-successional habitats. Habitat area for lynx and ES birds was projected to be higher than the BAU-Reference case under most scenarios, although it is important to note that reducing land use constraints had a positive effect on lynx habitat area but a negative effect on ES bird habitat. This difference emerged because the additional spruce-planted clearcuts under the no

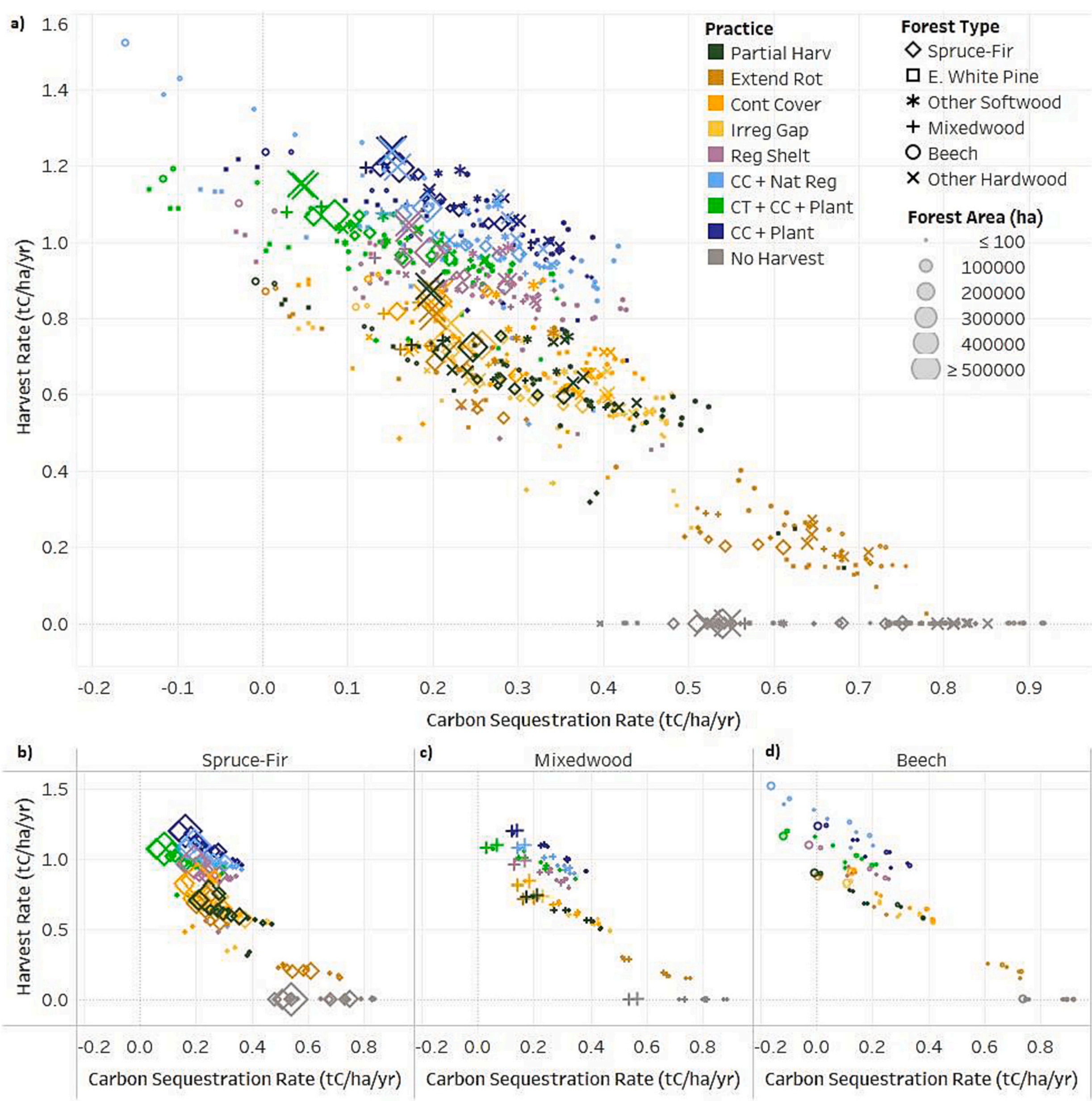

Fig. 5. Mean carbon sequestration (tC/ha/yr) and harvest rates (tC/ha/yr) by practice and initial forest type for (a) all forest types, (b) spruce-fir, (c) mixedwood, and (d) beech forests.

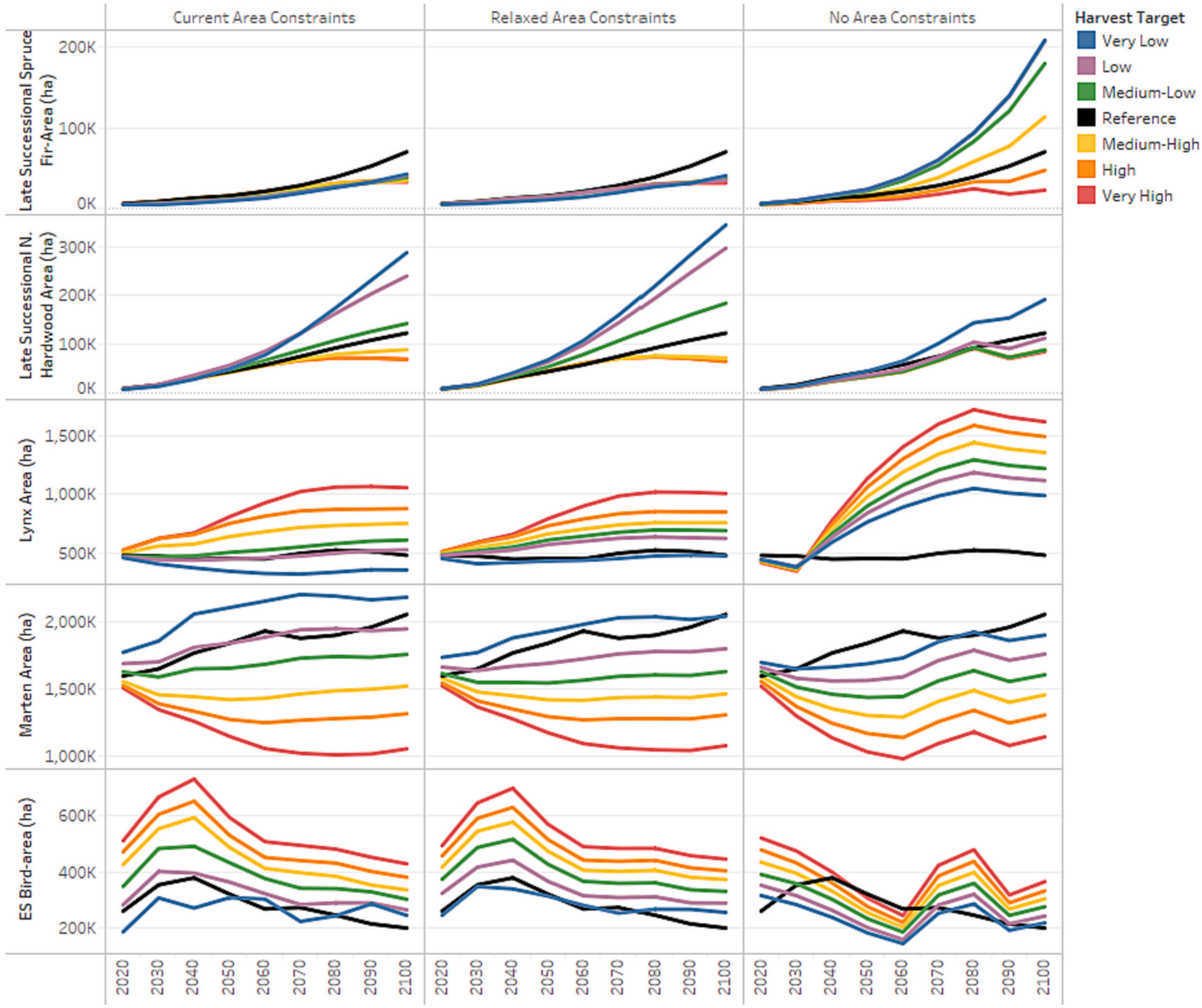

Fig. 6. Biodiversity indicator impacts under alternative average harvest targets and silvicultural practice constraints, 2020–2100.

area constraints scenarios benefited lynx habitat, which requires the species composition of regenerating forest to be >50% spruce-fir to be suitable, whereas ES bird habitat is benefited by naturally regenerated clearcuts.

In contrast to the ES habitats, marten habitat and LS forest were particularly sensitive to harvest level and only benefited from changes in forest management when coupled with lower targets. This trade-off occurs because more forestland was allocated to be harvested at higher harvest targets (Fig. 3), which resulted in the creation of more young forest benefitting ES habitats and less unharvested forest to benefit LS habitats (Fig. 6). Additionally, higher timber demand resulted in more land being allocated to intensive, even-aged treatments (e.g., regular shelterwood), resulting in a lower mean-age forest than the less intensive, uneven-aged treatments (e.g., irregular gap).

The biodiversity indicators followed similar patterns under the current and relaxed area limit scenarios, with relative changes for all but the LS hardwood area being slightly larger for the current area constraint scenarios (Fig. 6). In contrast, the removal of area constraints resulted in differing outcomes. The shift to a landscape dominated by intensively-managed clearcuts planted with spruce and unharvested forest resulted in notable benefits to spruce-fir associated habitats (i.e., LS spruce-fir and lynx habitat) but not habitats associated with other forest compositions (i.e., ES bird, LS N. hardwood, and marten). Reducing land use constraints positively affected LS forest because of the increase in unharvested forest, but had a limited effect on marten habitat because of the shift in treated area from uneven-aged management practices, some of which would have met the criteria for marten habitat, to clearcuts.

Interestingly, under the BAU-reference scenario, the area for LS spruce-fir forest and marten habitat were high relative to many of our other scenarios. For LS spruce-fir, suitable habitat only increased above BAU when harvests were 2.2 MMTC/yr or less, combined with no area limits. In all other scenarios, the average area for that indicator decreases by −29% to −50% compared to BAU. For Marten habitat, the only scenarios where habitat area increased compared to the BAU were when the very low harvest target was combined with current (+11%) or relaxed (+4%) area limits. For all other scenarios, the area suitable for marten declined by −1 to −38%, with the rate of decline increasing with harvest level. However, it should be noted that the mean BAU marten area is about 1.9 million ha, which is by far the greatest area of suitable habitat across the five indicators, with ES bird being a distant second with 0.27 million ha.

3.5. Long-run outcomes from alternative forest management objectives

The estimates presented above illustrate how adjusting the distribution of practices to meet different forest management objectives and constraints can lead to a range of outcomes regarding forest fiber, carbon, and biodiversity. While it was possible to improve some of these indicators relative to the BAU-reference case, it was not possible to simultaneously increase all 8 metrics of interest for this study (Table 3). We found several cases where timber, carbon, and net revenue could simultaneously increased relative to the BAU under higher (MH to VH) harvest levels in which 2 of the 5 biodiversity indicators (i.e., lynx and ES bird) also increased. At lower harvest levels (VL to ML), it was possible for carbon and 3 of the biodiversity indicators to increase simultaneously, but not also timber and net revenue. LS spruce-fir was the most limited in terms of opportunity to increase relative to BAU, which only occurred under the combination of lower harvest levels and no land use constraints.

Although forest carbon sequestration and timber harvest were strongly negatively correlated (−0.91) (Fig. 5, Table S4), there was only one scenario (i.e., *Max C - Current Area Lim - VH Harv*) that sequestration did not increase over BAU. We estimated forest C could increase by 15–25% by changing the distribution of management practices to a broader mix of intensive and extensive practices while still maintaining a harvest target like the reference case. In addition, we found that it could be possible to increase harvests by >20% above BAU with a predominantly positive effect (−3% to +11%) on forest C depending on the stringency of the land use change constraints, noting that even where forest C declines relative to BAU, it is still an overall net sink. On the other hand, reducing annual harvests by 26% could result in a 30%–46% increase in forest C sequestration, although reducing harvests could also result in a 24–29% loss in net revenue to landowners if they were not compensated for the carbon gains.

Harvest levels and net revenue from the sale of timber in our study area were estimated to be highly correlated ($r = 0.99$), as greater sawlog, pulp, and biomass removal will yield greater overall profits for forestland owners (assuming there are no other sources of revenue for their forest). On average, landowners collectively receive about $65 million in revenue per annum, equivalent to an average of $1380 ha^{-1} for harvested forestland. These metrics would obviously change if landowners were also compensated for the additional carbon or other ecosystem services that they produce. For example, landowners may be willing to shift their management practices and reduce harvests to the L to VL targets if they received carbon payments of $7 to $19/tCO2e for the additional C sequestered in response to this management change, as these payments would allow them to maintain the BAU-reference net revenue levels.

There are also clear tradeoffs between the different harvest and carbon benefits and the five biodiversity indicators. Forest carbon sequestration was positively correlated with marten (0.81), LS northern hardwood (0.62), and LS spruce fir (0.61) habitat area, but negatively correlated with lynx (−0.29) and ES bird habitat (−0.93). As expected, harvest level had an opposing relationship with habitat area, such that ES bird (0.83) and lynx (0.64) were positively correlated with increased harvesting, while marten (−0.97), LS northern hardwood (−0.80) and LS spruce fir (−0.39) were negatively correlated. These effects can largely be explained by the increase in intensive even-aged management under higher harvest levels, as ES bird and lynx habitat are associated with young, regenerating forest conditions. Interestingly, we found one scenario where it was possible to achieve increases in timber, carbon, and three of the five biodiversity indicators (*Max C - No Area Lim - MH Harv*) relative to BAU, which was a result of a relatively balanced distribution of intensively managed clearcuts that benefit lynx and ES bird and set asides that had a higher amount of LS spruce-fir.

4. Discussion

Northern Maine's forest carbon stocks were estimated to increase over the next 80 years across all modeled scenarios as they continue to

Table 3
Average key model outputs for Northern Maine forest management study scenarios, 2020–2100.

Scenario	Forest C Seq (MMtC/yr)	Timber Harvest (MMtC/yr)	Net Revenue (Mil $/yr)	LS Spruce-Fir Area (k ha)	LS NHW Area (k ha)	Lynx Area (k ha)	Marten Area (k ha)	ES Bird Area (k ha)
BAU-Reference	0.92	2.15	$65.5	34.4	69.4	477	1,870	272
Percent Change from BAU-Reference Case								
Max C - Current Area Lim - VL Harv	30%	-26%	-29%	-38%	90%	-24%	11%	-1%
Max C - Current Area Lim - L Harv	26%	-16%	-17%	-38%	73%	1%	-1%	18%
Max C - Current Area Lim - ML Harv	20%	-7%	-6%	-39%	15%	13%	-10%	39%
Max C - Current Area Lim - MH Harv	15%	2%	5%	-36%	-17%	40%	-21%	57%
Max C - Current Area Lim - H Harv	8%	12%	16%	-33%	-27%	62%	-29%	74%
Max C - Current Area Lim - VH Harv	-3%	21%	23%	-38%	-27%	85%	-38%	94%
Max C - Relaxed Area Lim - VL Harv	39%	-26%	-26%	-37%	138%	-6%	4%	5%
Max C - Relaxed Area Lim - L Harv	33%	-16%	-15%	-35%	109%	22%	-7%	23%
Max C - Relaxed Area Lim - ML Harv	27%	-7%	-2%	-31%	42%	31%	-15%	43%
Max C - Relaxed Area Lim - MH Harv	20%	2%	10%	-29%	-24%	42%	-22%	60%
Max C - Relaxed Area Lim - H Harv	11%	12%	18%	-31%	-27%	57%	-28%	73%
Max C - Relaxed Area Lim - VH Harv	1%	21%	26%	-40%	-27%	78%	-37%	91%
Max C - No Area Lim - VL Harv	46%	-26%	-24%	158%	42%	69%	-4%	-15%
Max C - No Area Lim - L Harv	39%	-16%	-14%	157%	-6%	87%	-10%	-6%
Max C - No Area Lim - ML Harv	32%	-7%	-5%	125%	-20%	101%	-16%	7%
Max C - No Area Lim - MH Harv	25%	2%	5%	51%	-20%	120%	-23%	18%
Max C - No Area Lim - H Harv	18%	12%	15%	-23%	-20%	139%	-30%	28%
Max C - No Area Lim - VH Harv	11%	21%	24%	-51%	-22%	156%	-37%	41%

< -30%	-15 to -30%	0 to -15%	0 to 15%	15% to 30%	More than 30%

recover from historically intensive harvest and natural disturbances like the spruce budworm (*Choristoneura fumiferana*) outbreak of the 1980s (Chen et al., 2019). The rate of forest growth and carbon sequestration typically declines over time though as no- and low- harvest intensity forests in our study area mature. These findings are similar to other studies of the future productivity of Maine and New England forests (Duveneck et al., 2017; Nevins et al., 2021; Simons-Legaard et al., 2021; Zhao et al., 2022, 2023). Global- and national-level studies have also found that forest carbon stocks are likely to accumulate over the next century due to forest regrowth (Pugh et al., 2019), improved forest management (Daigneault et al., 2022), and continued reliance on high yield plantation forests to meet timber demands (Nepal et al., 2019), amongst other things.

Although carbon sequestration is almost always positive (i.e., forests are a net sink) across our simulation period for all scenarios, the estimates decrease with higher annual harvest targets. This is primarily because practices with low removal rates retain higher amounts of relatively fast-growing (and sequestering) biomass (see Table 1), which is consistent with other studies of the region's forests (e.g., Russell-Roy et al., 2014; Puhlick et al., 2016, 2020). For example, Gunn and Buchholz (2018) found that uneven-aged stands have greater carbon stocks than even-aged forests, while Ford and Keeton (2017) indicated that carbon increased with the forest's structural complexity, which might mostly depend on species composition following a harvest (Puhlick et al., 2022). In addition, the conversion of standing biomass can result in carbon losses (Smith et al., 2006; Johnston and Radeloff, 2019). For Maine, about 75% of the carbon harvested and milled into HWPs is released during the production and disposal process (Wei et al., 2023; Bai et al., 2020).

Our model simulations estimated that the distribution of forest practices would likely have to deviate from the historical BAU-reference case to maximize Maine's forest C potential. The state's forests are currently managed primarily as partial (50%) and shelterwood (25%) harvest regimes, with <10% of the area clearcut. This distribution has been relatively consistent over the past 30 years (MFS, 2022a), and was spurred via the implementation of the Forest Practices Act (FPA) that was implemented in 1991 and limited the size of clearcuts (MFS, 1995; Jin and Sader, 2006), although the economics of harvesting, hauling, and manufacturing wood products in the Northeast has also changed over this time as well (Irland, 2018). As a result, the state may have to consider policy incentives such as carbon pricing or subsidizing intermediate treatments and/or modifying existing forest policies if it wishes to efficiently increase carbon sequestration rates.

A lot of the regional forest modeling literature has focused on evaluating how forest carbon is impacted by different silvicultural practices (e.g. Puhlick et al., 2020, 2022), but not always on how it impacts overall harvest levels and potential financial returns to landowners. That is, while previous studies may have found that less intensive harvesting practices can increase forest carbon at a stand-level (e.g. Puhlick et al., 2020, 2022), they generally did so without fully accounting for the potential loss in timber volume required to achieve this result at a landscape-level. Like us, Nunery and Keeton (2010) found that C sequestration was significantly greater for the "no harvest" scenario compared to any of the active management options, and that treatments with high structural retention and decreased harvest frequency stored the greatest amounts of carbon. Meyer et al. (2022) estimated that that increasing stocking on half of Maine's inadequately stocked forestland could increase carbon sequestration by 28%, while shifting more land to wildlife reserves could increase sequestration by an additional 15%, although it is uncertain how much harvests would change to achieve this. Likewise, Giffen et al. (2022) evaluated the impacts of "Exemplary Forestry" management in the Acadian forests of northern New England and concluded it is possible to increase carbon sequestration by about 26%, although timber supply would initially be reduced to allow the forest to mature and financial returns would decline relative to the status quo if the only source of revenue is timber returns and not sales of conservation easements or carbon credits. These previous findings are within the range of our estimates, which taken together suggest it is possible to increase forest carbon sequestration in northern Maine by 15–25% while still maintaining the current harvest level.

In addition to highlighting the additional sequestration capacity of Maine's forests, our results suggest there is ample opportunity to increase sequestration rates without sacrificing timber or net revenue, but not without some costs to wildlife habitat or biodiversity (Table 3). In general, we found that maximizing carbon sequestration is more likely to result in co-benefits to early-successional habitats than to mid- or late-successional habitats in Maine. As early-successional habitats have been on the decline in New England, a carbon-focused shift in management could provide important habitat for disturbance-dependent songbirds in particular (Hunter et al., 2001). In contrast, there appears to be limited compatibility between carbon-focused forest management and late-successional habitats, particularly spruce-fir forest, without an associated increase in reserve lands. As residents of the Northern Forest region have strong positive associations with late-successional forest for their aesthetic and cultural values (Enck and Odato, 2008), careful consideration will be needed to ensure the persistence and accessibility of this already scarce forest type in policies that encourage carbon-focused forestry. Similarly, Harris and Betts (2023) found when comparing alternative land sparing and sharing regimes in the Pacific Northwest US that it was not possible to simultaneously maximize biodiversity, carbon, and timber via any management practice combination, and ultimately recommend a strategy that includes both, such as potentially accomplished through the triad management approach (Himes et al., 2022).

Like many states, Maine does not have any policies or regulations that explicitly target forest carbon sequestration. Current policies and programs related to managing the state's forests include regulations such as the FPA, financial incentives like the Tree Growth Tax Law (TGLT), landowner education programs, and a statewide forest inventory and monitoring program led by the Maine Forest Service (Soucy et al., 2021). Conservation finance initiatives such as the Land for Maine's Future program can help preserve forestland that provides multiple ecosystem service values, including carbon and timber. While we found in our analysis that Maine's forests can sequester more carbon if landowners can diversify their practices across the landscape, current regulations like the FPA constrain what landowners can do, largely through the restrictions on clearcut harvesting. The original FPA was amended in the early 2000s to allow qualified landowners to conduct "outcome-based forestry" (OBF) by implementing diverse management practices to achieve a wide set of forestry objectives, which could potentially include increasing forest carbon sequestration. However, OBF has a relatively high barrier to entry and thus only a few large landowners have adopted it. In addition, the TGTL was established to incentivize the production of commercial forest products, for which carbon sequestration on its own does not qualify. Thus, some of Maine's policies could be amended to make it easier for landowners to receive financial assistance for and/or implement climate-smart forestry practices.

Maine's landowners have the option to participate in compliance (e.g., CARB) and voluntary (e.g., Family Forest Carbon Program) forest offset markets, but only about 3% of the state's total forest area is enrolled in a program (Truesdale, 2020). These carbon markets can be restrictive and have high transaction costs, which is why the Maine Forest Carbon Task Force (2021) suggested alternative means of incentivizing forest carbon. These include increasing technical assistance to managers focused on NCS activities and offering long-term financial incentives for landowners to implement specific silvicultural practices. As there are already some financial assistance programs offered at the federal level (e.g., NRCS), and voluntary forest carbon programs continue to evolve with varying methodologies and incentive products, states like Maine should consider working in partnership with external entities to develop a credit-based or practice-oriented carbon program that can be tailored specifically to the unique characteristics of state's forestry sector. As with all forest carbon programs, careful attention will be required to ensure any new initiatives have minimal transaction costs, the practices implemented are indeed additional and can be adequately measured, monitored, and verified, and that funds are distributed efficiently.

Increasing Maine landowner interest in adopting forest NCS also depends on the existence of financially viable markets for wood of all grades, including biomass. These markets can further incentivize forest managers to practice sustainable forestry and silviculture in complex, uneven-aged, mixed-species forests like Maine, while also improving their bottom line. While Maine's forests have experienced relatively large market and policy shocks over the past few decades, there is still a robust and innovative forest products sector that is a key contributor to Maine's rural economy, particularly northern Maine (Bailey and Green, 2021). Initiatives like FOR/ME (2018) are targeting options to sustainably grow the sector, and ideally this can happen in tandem with opportunities to increase forest carbon or addtiioanl forest ecosystem services like biodiversity through active forest management. In addition, while a "no harvest" approach can have significant carbon sequestration benefits as forests continue to grow, these stands will eventually reach a mature state and likely be at higher risk of damage from climate, pest, and other natural disturbances due to their already high relative density (Woodall and Weiskittel, 2021). Further, while northern Maine's forests are low risk for land use change (Dewitz & USGS, 2021), promoting access to diverse timber, carbon, and biodiversity markets can help ensure that these forests are kept as working forests.

Our methods and analysis have some notable limitations. First, we use a relatively simplistic scenario approach where the objective is to maximize forest carbon under modeler specified harvest target and forest management constraints. Future work on this topic could incorporate more detailed narratives and variance in assumptions for the scenario development (e.g., O'Neill et al., 2020). Second, while we do calculate the net returns to landowners for the different management options imposed, the emphasis of this present analysis was on the physical tradeoffs between key ecosystem services associated with different forest management practices as that is the primary interest of many state-level decision makers. An alternative approach would be to specify the model objective as a profit maximization function and then evaluate the potential impacts under various timber demand and carbon price assumptions (e.g., Daigneault et al., 2022; Wade et al., 2022). Third, we did not present a detailed model sensitivity analysis beyond evaluating the effect of varying the constraints in our scenarios. Future research could conduct a more formal global parameter sensitivity analysis to account for uncertainties in model outputs, particularly with respect to carbon accounting or economic returns (e.g., Tian et al., 2018; Sohngen et al., 2019). Fourth, while we did use a region-specific estimate to convert timber into HWP C, we assumed that the product mix continued to follow the historical trend (Wei et al., 2023). Additional analysis could account for a wider suite of HWPs, particularly those with longer half-lifes, that could be produced in the future (e.g., Hurmekoski et al., 2018). Fifth, our biodiversity indicators are based on evaluating the area of suitable habitat, which does not directly translate to occurrence of target species. Sixth, we assume constant productivity and harvest and wood processing technology over the entire simulation, likely resulting in more conservative forest carbon estimates (Mendelsohn and Sohngen, 2019). Finally, future work could investigate the coupling effect that climate change and natural disturbance impacts could have on regional forest ecosystem services (e.g., Duveneck and Thompson, 2019; Baker et al., 2023).

5. Conclusion

Our integrated forest landscape analysis indicates that northern Maine's working, primarily commercial forests could increase their forest carbon stocks and sequestration while continuing to supply a sustainable amount of fiber to the forest products sector. Timber production is currently and likely to remain a primary objective for many landowners in northern Maine forest landscapes. However, forest managers face increasing pressures and incentives to manage for a broad suite of ecosystem services while also meeting sustainable timber supply and profitability targets. Based on our 19 scenarios examined, we were unable to find a case where all timber, carbon, and biodiversity indicators simultaneously increased relative to the baseline reference case, which followed historical harvest and management trends. This highlights the challenge of achieving multiple objectives in a complex forest landscape management while also indicating that although multiple allocation options are technically possible, those options fall within a relatively large decision space for balancing objectives and determining trade-offs. For each of our timber harvest targets, forest managers can implement a range of silvicultural treatments that result in a different distribution of economic and environmental benefits. Importantly, we find that it is possible to maintain harvests in our study area and increase carbon sequestration by 15–25% over the reference case through landscape-level shifts in forest management. Thus, our framework shows that Maine's forests can achieve a key subset of objectives, provided landowners have clear policy, social, and economic signals that enable them to vary their management strategies.

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CRediT authorship contribution statement

Adam Daigneault: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Erin Simons-Legaard:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Aaron Weiskittel:** Conceptualization, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Austin, K.G., Baker, J.S., Sohngen, B.L., Wade, C.M., Daigneault, A., Ohrel, S.B., Bean, A., 2020. The economic costs of planting, preserving, and managing the world's forests to mitigate climate change. Nat. Commun. 11 (1), 5946.

Bai, X., Daigneault, A., Fernandez, I., Frank, J., Hayes, D., Johnson, B., et al., 2020. State of Maine's Carbon Budget, 2006-2016 (version 1.0). Center for Research on Sustainable Forests Technical Report. https://crsf.umaine.edu/forest-climate-change-initiative/carbon-budget/.

Bailey, M., Crawley, A., 2023. The economic contribution of logging and trucking in Maine. In: EDA Center at University of Maine Staff Paper 2023-109. https://maineloggers.com/wp-content/uploads/2023/02/Logging-and-Trucking-Impact-02.01.23-1.pdf.

Bailey, M., Green, S., 2021. The Economic Contribution of Maine's Forest Products Industry: 2019. University of Maine Margaret Chase Smith Policy Center Technical Report prepared for the Maine Forest Products Council. https://digitalcommons.library.umaine.edu/mcspc_ecodev_articles/19.

Baker, J.S., Van Houtven, G., Phelan, J., Latta, G., Clark, C.M., Austin, K.G., Martinich, J., 2023. Projecting US forest management, market, and carbon sequestration responses to a high-impact climate scenario. Forest Policy Econ. 147, 102898.

Bose, A.K., Weiskittel, A., Wagner, R.G., Kuehne, C., 2016. Assessing the factors influencing natural regeneration patterns in the diverse, multi-cohort, and managed forests of Maine, USA. J. Veg. Sci. 27 (6), 1140–1150.

Brooks, R.T., 2003. Abundance, distribution, trends, and ownership patterns of early-successional forests in the northeastern United States. For. Ecol. Manag. 185, 65–74.

Butler, B.J., Butler, S.M., Caputo, J., Dias, J., Robillard, A., Sass, E.M., 2021. Family forest ownerships of the United States, 2018: results from the USDA Forest Service, National Woodland Owner Survey. In: Gen. Tech. Rep. NRS-199. U.S. Department of Agriculture, Forest Service, Northern Research Station, Madison, WI. https://doi.org/10.2737/NRS-GTR-199, 52 p.

Chen, C., Wei, X., Weiskittel, A., Hayes, D.J., 2019. Above-ground carbon stock in merchantable trees not reduced between cycles of spruce budworm outbreaks due to changing species composition in spruce-fir forests of Maine, USA. For. Ecol. Manag. 453, 117590.

Daigneault, A., Simons-Legaard, E., Birthisel, S., Carroll, J., Fernandez, I., Weiskittel, A., 2021. Maine Forestry and Agriculture Natural Climate Solutions Mitigation Potential. Final Report. University of Maine Center for Research on Sustainable Forests, Orono (ME). https://crsf.umaine.edu/wp-content/uploads/sites/214/2021/08/UMaine-NCS-Final-Report_final_8.4.21.pdf.

Daigneault, A., Baker, J.S., Guo, J., Lauri, P., Favero, A., Forsell, N., Sohngen, B., 2022. How the future of the global forest sink depends on timber demand, forest management, and carbon policies. Glob. Environ. Chang. 76, 102582.

Dewitz, J., U.S. Geological Survey, 2021. National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021). U.S. Geological Survey data release. https://doi.org/10.5066/P9KZCM54.

Díaz, S., Hector, A., Wardle, D.A., 2009. Biodiversity in forest carbon sequestration initiatives: not just a side benefit. Curr. Opin. Environ. Sustain. 1 (1), 55–60.

Domke, G.M., Walters, B.F., Giebink, C.L., Greenfield, E.J., Smith, J.E., Nichols, M.C., Knott, J.A., Ogle, S.M., Coulston, J.W., Steller, J., 2023. Greenhouse Gas Emissions and Removals from Forest Land, Woodlands, Urban Trees, and Harvested Wood Products in the United States, 1990–2021. U.S. Department of Agriculture Forest Service Resource Bulletin WO-101, Washington (DC). https://doi.org/10.2737/WO-RB-101.

Dugan, A.J., Lichstein, J.W., Steele, A., Metsaranta, J.M., Bick, S., Hollinger, D.Y., 2021. Opportunities for forest sector emissions reductions: a state-level analysis. Ecol. Appl. 31 (5), e02327.

Duveneck, M.J., Thompson, J.R., 2019. Social and biophysical determinants of future forest conditions in New England: effects of a modern land-use regime. Glob. Environ. Chang. 55, 115–129.

Duveneck, M.J., Thompson, J.R., Gustafson, E.J., Liang, Y., de Bruijn, A.M., 2017. Recovery dynamics and climate change effects to future New England forests. Landsc. Ecol. 32, 1385–1397.

Enck, J., Odato, M., 2008. Public attitudes and affective beliefs about early- and late-successional stages of the Great Northern Forest. J. For. 106 (7), 388–395.

Erb, K.H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Luyssaert, S., 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553 (7686), 73–76.

Fahey, T.J., Woodbury, P.B., Battles, J.J., Goodale, C.L., Hamburg, S.P., Ollinger, S.V., Woodall, C.W., 2010. Forest carbon storage: ecology, management, and policy. Front. Ecol. Environ. 8 (5), 245–252.

Fargione, J.E., Bassett, S., Boucher, T., Bridgham, S.D., Conant, R.T., Cook-Patton, S.C., Griscom, B.W., 2018. Natural climate solutions for the United States. Sci. Adv. 4 (11), eaat1869.

Ford, S.E., Keeton, W.S., 2017. Enhanced carbon storage through management for old-growth characteristics in northern hardwood-conifer forests. Ecosphere 8 (4), e01721.

Forest Opportunity Roadmap/Maine (FOR/ME), 2018. Vision And Roadmap for Maine's Forest Products Sector. https://formaine.org/wp-content/uploads/2020/09/FORMaine_Report_DL_041119.pdf.

Germain, R., Regula, J., Bick, S., Zhang, L., 2019. Factors impacting logging costs: a case study in the northeast, US. For. Chron. 95 (1), 16–23.

Giffen, R.A., Ryan, C.M., Belair, E.P., Pounch, M.A., Brown, S., 2022. Storing more carbon by improving forest management in the Acadian Forest of New England, USA. Forests 13 (12), 2031.

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Fargione, J., 2017. Natural climate solutions. Proc. Natl. Acad. Sci. 114 (44), 11645–11650.

Gunn, J.S., Buchholz, T., 2018. Forest sector greenhouse gas emissions sensitivity to changes in forest management in Maine (USA). For. Int. J. For. Res. 91 (4), 526–538.

Gustafson, E.J., Shifley, S.R., Mladenoff, D.J., Nimerfro, K.K., He, H.S., 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Can. J. For. Res. 30 (1), 32–43.

Hagan, J.M., Meehan, A.L., 2002. The effectiveness of stand-level and landscape-level variables for explaining bird occurrence in an industrial forest. For. Sci. 48 (2), 231–242.

Hagan, J.M., McKinley, P.S., Meehan, A.L., Grove, S.L., 1997. Diversity and abundance of Landbirds in a northeastern industrial forest. J. Wildl. Manag. 61 (3), 718–735.

Harris, S.H., Betts, M.G., 2023. Selecting among land sparing, sharing and triad in a temperate rainforest depends on biodiversity and timber production targets. J. Appl. Ecol. 60 (4), 737–750.

Hiesl, P., Benjamin, J.G., Roth, B.E., 2015. Evaluating harvest costs and profit of commercial thinnings in softwood stands in west-Central Maine: a case study. For. Chron. 91 (2), 150–160.

Hiesl, P., Crandall, M.S., Weiskittel, A., Benjamin, J.G., Wagner, R.G., 2017. Evaluating the long-term influence of alternative commercial thinning regimes and harvesting systems on projected net present value of precommercially thinned spruce–fir stands in northern Maine. Can. J. For. Res. 47 (2), 203–214.

Himes, A., Betts, M., Messier, C., Seymour, R., 2022. Perspectives: thirty years of triad forestry, a critical clarification of theory and recommendations for implementation and testing. For. Ecol. Manag. 510, 120103.

Hunter, W.C., Buehler, D.A., Canterbury, R.A., Confer, J.L., Hamel, P.B., 2001. Conservation of disturbance-dependent birds in eastern North America. Wildl. Soc. Bull. 29, 440–455.

Hurmekoski, E., Jonsson, R., Korhonen, J., Jänis, J., Mäkinen, M., Leskinen, P., Hetemäki, L., 2018. Diversification of the forest industries: role of new wood-based products. Can. J. For. Res. 48 (12), 1417–1432.

Irland, L.C., 2018. Maine's public estate and conservation lands: brief history and assessment. Maine Policy Rev. 27 (2), 11–29.

Irland, L.C., 2020. From Wilderness to Timberland to Vacationland to Ecosystem: Maine's Forests, 1820–2020. Maine Policy Rev. 29 (2), 45–56.

Jin, S., Sader, S.A., 2006. Effects of forest ownership and change on forest harvest rates, types and trends in northern Maine. For. Ecol. Manag. 228 (1–3), 177–186.

Johnston, C.M., Radeloff, V.C., 2019. Global mitigation potential of carbon stored in harvested wood products. Proc. Natl. Acad. Sci. 116 (29), 14526–14531.

Kenefic, L.S., Bataineh, M., Wilson, J.S., Brissette, J.C., Nyland, R.D., 2014. Silvicultural rehabilitation of cutover mixedwood stands. J. For. 112 (3), 261–271.

Kilgore, M.A., Ellefson, P.V., Funk, T.J., Frey, G.E., 2018. Private forest owners and property tax incentive programs in the United States: a national review and analysis of ecosystem services promoted, landowner participation, forestland area enrolled, and magnitude of tax benefits provided. Forest Policy Econ. 97, 33–40.

Koirala, A., Kizha, A.R., De Urioste-Stone, S.M., 2017. Policy recommendation from stakeholders to improve forest products transportation: a qualitative study. Forests 8 (11), 434.

Kuehne, C., Weiskittel, A., Simons-Legaard, E., Legaard, K., 2019. Development and comparison of various stand- and tree-level modeling approaches to predict harvest occurrence and intensity across the mixed forests in Maine, northeastern US. Scand. J. For. Res. 34 (8), 739–750.

Legaard, K.R., Sader, S.A., Simons-Legaard, E.M., 2015. Evaluating the impact of abrupt changes in forest policy and management practices on landscape dynamics: analysis of a Landsat image time series in the Atlantic Northern Forest. PLoS One 10 (6), e0130428.

Legaard, K., Simons-Legaard, E., Weiskittel, A., 2020. Multi-objective support vector regression reduces systematic error in moderate resolution maps of tree species abundance. Remote Sens. 12 (11), 1739.

Littlefield, C.E., D'Amato, A.W., 2022. Identifying trade-offs and opportunities for forest carbon and wildlife using a climate change adaptation lens. Conserv. Sci. Pract. 4 (4), e12631.

Litvaitis, J.A., 2003. Shrublands and early-successional forests: critical habitats dependent on disturbance in the northeastern United States. For. Ecol. Manag. 185, 1–4.

MacLean, M.G., Duveneck, M.J., Plisinski, J., Morreale, L.L., Laflower, D., Thompson, J.R., 2021. Forest carbon trajectories: consequences of alternative land-use scenarios in New England. Glob. Environ. Chang. 69, 102310.

Maine Climate Council, 2020. Maine Won't Wait: A Four-Year Plan for Climate Action. https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/MaineWontWait_December2020.pdf.

Maine Department of Environmental Protection (MEDEP), 2022. Ninth biennial report on Progress toward greenhouse gas reduction goals. In: Augusta (ME): Report to the Joint Standing Committee on Environment and Natural Resources 130th Legislature, Second Session. https://www.maine.gov/climateplan/sites/maine.gov.climateplan/files/inline-files/9th_GHG_Report_FINAL%20%282%29.pdf.

Maine Forest Carbon Task Force, 2021. Governor's Task Force on the Creation of a Forest Carbon Program. Final Report. Maine Governor's Office of Policy, Innovation and the Future, Augusta (ME). https://www.maine.gov/future/sites/maine.gov.future/files/inline-files/MaineForestCarbonTaskForce_FinalReport.pdf.

Maine Forest Service (MFS), 1995. An Evaluation of the Effects of the Forest Practices Act.

Maine Land Trust Network (MLTN), 2017. Land Trusts Work for Maine Report. MLTN Report, October 2017. https://mltn.org/wp-content/uploads/2019/01/land-trust-highlights.pdf.
Maine Office of Geographic Information Systems (MEGIS), 2023. Maine conserved lands. In: Maine GIS Data Catalog. Maine GIS SDE Server. https://hub.arcgis.com/datasets/a6797f12a07b4229bc2501d3741c98d4.
Maine Revenue Service (MRS), 2022. 2021 Municipal Valuation Return Statistical Summary. https://www.maine.gov/revenue/sites/maine.gov.revenue/files/inline-files/2021mvrstats.pdf.
Mendelsohn, R., Sohngen, B., 2019. The net carbon emissions from historic land use and land use change. J. For. Econ. 34 (3–4), 263–283.
Meyer, S.R., et al., 2022. New England's Climate Imperative: Our Forests as a Natural Climate Solution; Redding, CT, USA. Highstead Foundation report. https://highstead.net/library/forests-as-a-natural-climate-solution/.
Meyer, S.R., Cronan, C.S., Lilieholm, R.J., Johnson, M.L., Foster, D.R., 2014. Land conservation in northern New England: Historic trends and alternative conservation futures. Biol. Conserv. 174, 152–160.
MFS, 2014. 2013 Tree Growth Tax Law Audit Report. Maine ACF, Maine Forest Service. report No. PL 2011, Chapter 619, prepared for 125th Maine Legislature. https://www.maine.gov/dacf/mfs/publications/reports/2013_tgtl_audit_report.pdf.
MFS, 2022a. Silvicultural Activity Reports. https://www.maine.gov/dacf/mfs/publications/annual_reports.html.
MFS, 2022b. Stumpage Price Reports. https://www.maine.gov/dacf/mfs/publications/annual_reports.html.
MFS, 2022c. Wood Processor Reports. https://www.maine.gov/dacf/mfs/publications/annual_reports.html.
Mladenoff, D.J., 2004. LANDIS and forest landscape models. Ecol. Model. 180 (1), 7–19.
Moomaw, W.R., Masino, S.A., Faison, E.K., 2019. Intact forests in the United States: Proforestation mitigates climate change and serves the greatest good. Front. For. Glob. Change 2.
Nepal, P., Korhonen, J., Prestemon, J.P., Cubbage, F.W., 2019. Projecting global planted forest area developments and the associated impacts on global forest product markets. J. Environ. Manag. 240, 421–430.
Nevins, M.T., D'Amato, A.W., Foster, J.R., 2021. Future forest composition under a changing climate and adaptive forest management in southeastern Vermont, USA. For. Ecol. Manag. 479, 118527.
Nunery, J.S., Keeton, W.S., 2010. Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. For. Ecol. Manag. 259 (8), 1363–1375.
O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Pichs-Madruga, R., 2020. Achievements and needs for the climate change scenario framework. Nat. Clim. Chang. 10 (12), 1074–1084.
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333 (6045), 988–993.
Pan, W., Kim, M.K., Ning, Z., Yang, H., 2020. Carbon leakage in energy/forest sectors and climate policy implications using meta-analysis. Forest Policy Econ. 115, 102161.
Patton, R.M., Kiernan, D.H., Burton, J.I., Drake, J.E., 2022. Management trade-offs between forest carbon stocks, sequestration rates and structural complexity in the Central Adirondacks. For. Ecol. Manag. 525, 120539.
Payer, D.C., Harrison, D.J., 2003. Influence of forest structure on habitat use by American marten in an industrial forest. For. Ecol. Manag. 179, 145–156.
Pugh, T.A., Lindeskog, M., Smith, B., Poulter, B., Arneth, A., Haverd, V., Calle, L., 2019. Role of forest regrowth in global carbon sink dynamics. Proc. Natl. Acad. Sci. 116 (10), 4382–4387.
Puhlick, J.J., Weiskittel, A.R., Fernandez, I.J., Fraver, S., Kenefic, L.S., Seymour, R.S., Brissette, J.C., 2016. Long-term influence of alternative forest management treatments on total ecosystem and wood product carbon storage. Can. J. For. Res. 46 (11), 1404–1412.
Puhlick, J.J., Weiskittel, A.R., Kenefic, L.S., Woodall, C.W., Fernandez, I.J., 2020. Strategies for enhancing long-term carbon sequestration in mixed-species, naturally regenerated Northern temperate forests. Carbon Management 11 (4), 381–397.
Puhlick, J.J., Weiskittel, A.R., Fernandez, I.J., Solarik, K.A., Sleep, D.J., 2022. Evaluation of projected carbon accumulation after implementing different forest management treatments in mixed-species stands in northern Maine. Carbon Management 13 (1), 190–204.
Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Tavoni, M., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168.
Roebroek, C.T., Duveiller, G., Seneviratne, S.I., Davin, E.L., Cescatti, A., 2023. Releasing global forests from human management: how much more carbon could be stored? Science 380 (6646), 749–753.
Russell-Roy, E.T., Keeton, W.S., Pontius, J.A., Kerchner, C.D., 2014. Rehabilitation forestry and carbon market access on high-graded northern hardwood forests. Can. J. For. Res. 44 (6), 614–627.
Scheller, R.M., Domingo, J.B., Sturtevant, B.R., Williams, J.S., Rudy, A., Gustafson, E.J., Mladenoff, D.J., 2007. Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecol. Model. 201 (3–4), 409–419.
Scheller, R.M., Mladenoff, D.J., 2004. A forest growth and biomass module for a landscape simulation model, LANDIS: design, validation, and application. Ecol. Model. 180 (1), 211–229.
Simons-Legaard, E.M., Harrison, D.J., Krohn, W.B., Vashon, J.H., 2013. Canada lynx occurrence and forest management in the Acadian Forest. J. Wildl. Manag. 77 (3), 567–578.
Simons-Legaard, E., Legaard, K., Weiskittel, A., 2021. Projecting complex interactions between forest harvest and succession in the northern Acadian Forest region. Ecol. Model. 456, 109657.
Skytt, T., Englund, G., Jonsson, B.G., 2021. Climate mitigation forestry—temporal trade-offs. Environ. Res. Lett. 16 (11), 114037.
Smith, J.E., Heath, L.S., Skog, K.E., Birdsey, R.A., 2006. Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States. USDA Forest Service, Northeastern Research Station. General Technical Report NE-343.
Sohngen, B., Salem, M.E., Baker, J.S., Shell, M.J., Kim, S.J., 2019. The influence of parametric uncertainty on projections of forest land use, carbon, and markets. J. For. Econ. 34 (1–2), 129–158.
Soucy, A., De Urioste-Stone, S., Rahimzadeh-Bajgiran, P., Weiskittel, A., McGreavy, B., 2021. Forestry professionals' perceptions of climate change impacts on the forest industry in Maine, USA. J. Sustain. For. 40 (7), 695–720.
Stevens, D., 2018. Historic and Predicted Wood Costs in Maine for Selected Species and Products. Final Report. J.W. Sewall, Old Town (ME). prepared for FOR/Maine (Forest Opportunity Roadmap/Maine). http://formaine.org/wp-content/uploads/2020/09/ME-Wood-Cost-Analysis-final-complete.pdf.
Thom, D., Keeton, W.S., 2020. Disturbance-based silviculture for habitat diversification: effects on forest structure, dynamics, and carbon storage. For. Ecol. Manag. 469, 118132.
Tian, X., Sohngen, B., Baker, J., Ohrel, S., Fawcett, A.A., 2018. Will US forests continue to be a carbon sink? Land Econ. 94 (1), 97–113.
Truesdale, A., 2020. Carbon offset projects: the experience in Maine. Maine Woodl. 45 (4), 4–5, 1.
US Department of Interior, 2008. Endangered and threatened wildlife and plants; revised critical habitat for the contiguous United States distinct population segment of the Canada lynx (*Lynx canadensis*); proposed rule. Fed. Regist. 73, 10860–10895.
US Environmental Protection Agency (USEPA), 2023. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021. U.S. Environmental Protection Agency. EPA 430-R-23-002. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-andsinks-1990-2021.
USDA Forest Service, 2021. Family forest (10+ acres) ownership characteristics: Maine, 2018. In: Res. Note NRS-278. U.S. Department of Agriculture, Forest Service, Northern Research Station, Madison, WI. https://doi.org/10.2737/NRS-RN-278, 2 p.
Wade, C.M., Baker, J.S., Jones, J.P., Austin, K.G., Cai, Y., de Hernandez, A.B., McCarl, B., 2022. Projecting the impact of socioeconomic and policy factors on greenhouse gas emissions and carbon sequestration in US Forestry and Agriculture. J. For. Econ. 37 (1), 127–131.
Walker, T., Daigneault, A., Giffen, R.A., Simons-Legaard, E., Allogio, J., Kenefic, L., Weiskittel, A., Lidstrom, Z., 2023. Can Northern Maine's Commercial Forests Store More Carbon Without Reducing Harvest? Final Report prepared for the Forest Carbon for Commercial Landowners Initiative. https://newenglandforestry.org/connect/publications/fccl/.
Wang, W.J., Thompson III, F.R., He, H.S., Fraser, J.S., Dijak, W.D., Spetich, M.A., 2018. Population dynamics has greater effects than climate change on tree species distribution in a temperate forest region. J. Biogeogr. 45 (12), 2766–2778.
Wei, X., Zhao, J., Hayes, D.J., Daigneault, A., Zhu, H., 2023. A life cycle and product type based estimator for quantifying the carbon stored in wood products. Carbon Balance Manag. 18 (1), 1.
Whitman, A.A., Hagan, J.M., 2007. An index to identify late-successional forest in temperate and boreal zones. For. Ecol. Manag. 246, 144–154.
Woodall, C.W., Weiskittel, A.R., 2021. Relative density of United States forests has shifted to higher levels over last two decades with important implications for future dynamics. Sci. Rep. 11 (1), 18848.
Zhang, X., Chen, J., Dias, A.C., Yang, H., 2020. Improving carbon stock estimates for in-use harvested wood products by linking production and consumption—a global case study. Environ. Sci. Technol. 54 (5), 2565–2574.
Zhao, J., Daigneault, A., Weiskittel, A., 2020. Forest landowner harvest decisions in a new era of conservation stewardship and changing markets in Maine, USA. Forest Policy Econ. 118, 102251.
Zhao, J., Daigneault, A., Weiskittel, A., 2022. Estimating regional timber supply and forest carbon sequestration under shared socioeconomic pathways: a case study of Maine, USA. PLOS Clim. 1 (5), e0000018.
Zhao, J., Daigneault, A., Weiskittel, A., Wei, X., 2023. Climate and socioeconomic impacts on Maine's forests under alternative future pathways. Ecol. Econ. 214, 107979.