FOREST CARBON

FOR COMMERCIAL LANDOWNERS REPORT

Can Northern Maine's Commercial Forests Store More Carbon Without Reducing Harvest?

REPORT PREPARED FOR
the Forest Carbon for Commercial Landowners Initiative

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FCCL STUDY GOAL

The FCCL project was designed to evaluate whether commercial forest landowners in Maine could increase carbon sequestration in the forest and in harvested wood products (HWPs) by employing various silvicultural practices that would cost-effectively mitigate greenhouse gas emissions while not reducing harvests over time.

LANDSCAPE-SCALE NORTHERN MAINE STUDY AREA

Our study considered 7.6 million acres of predominantly privately owned commercial forest lands in northern Maine. Under current management practices these lands are expected to provide net carbon sequestration estimated at 3.6 million metric tons of CO_2 equivalent (MtCO2e) per year over a 60-year time horizon while providing timber harvests of approximately 7 million green tons per year—equal to 7.3 MtCO2e—that support the northern Maine forest products sector and rural communities.

Photo by Charlie Reinertsen

INCREASED FOREST CARBON SEQUESTRATION AND STORAGE

The FCCL work suggests that landscape-scale adoption of certain silvicultural systems has the potential to increase carbon sequestration and storage in HWPs without reducing harvests. Silviculture with the potential to increase carbon sequestration and storage includes a variety of systems that rely on thinning to improve quality and growth rates and approaches that use clearcutting and planting combined with leaving other areas unharvested. Under assumptions that current trends continue in the forest products sector, we project that transitioning a greater share of northern Maine's commercial timberlands to these carbon-enhancing silvicultural systems over the coming decades has the potential to increase carbon sequestration in the forest and in HWPs by upwards of 20 percent compared with current management practices. This equates to an estimated 737,000 tons or more of additional CO2e per year across the 7.6-million-acre study area over the 60-year study horizon. This estimate understates sequestration for the alternative silvicultural practices that raise the proportion of sawlogs harvested. This was not modeled in our study.

COST-EFFECTIVE CLIMATE MITIGATION

As a basis for determining the cost-effectiveness of forest management as a carbon mitigation strategy in northern Maine, the study estimated the additional costs to landowners of implementing silviculture that sequesters more carbon. These costs appear competitive with other approaches for reducing carbon in the atmosphere. At the high end, landowners on average would need to be paid approximately $16/tCO2e to make it profitable for them to adopt alternative silvicultural systems that store more carbon. This equates to an average upfront payment of approximately $151 per acre. On a $/tCO2e basis, these costs are very competitive with other climate mitigation measures like solar and wind energy.

TRUE ADDITIONALITY/NO LEAKAGE

The transition to alternative silvicultural approaches can provide increased carbon that passes both the "additionality" and "leakage" tests. The additional carbon sequestration identified by our research would not have existed without active implementation by commercial landowners of the alternative silvicultural practices evaluated in this study. Adoption of these practices would provide meaningful climate benefits that are not vulnerable to the additionality critiques undermining some carbon offset projects—the claim that carbon would have been sequestered anyway even in the absence of an incentive payment, and that the offset therefore provides no real climate benefit. Furthermore, our projected carbon increases would be achieved by applying forest management approaches where average harvest levels could be maintained at current levels over the study's 60-year time horizon, thereby avoiding leakage, the problem where increased carbon sequestration in one region is negated by increased timber harvests and carbon emissions in another, again resulting in no net climate benefit.

NEW FOREST CARBON POLICY MODELING TOOL

The FCCL work has created a valuable tool for evaluating the opportunities and tradeoffs involved in deploying silviculture at a large landscape scale to achieve carbon goals. A key insight of our work has been to demonstrate that there are multiple ways of combining silvicultural systems across the landscape to increase carbon sequestration while maintaining harvest levels. Different mixes of silvicultural systems can provide different levels of increased sequestration across the landscape and in HWP storage. The mix of systems has implications for the provision of ecosystem services (e.g., wildlife/biodiversity) and economic benefits. Understanding these opportunities and tradeoffs is a critical task moving forward, which the FCCL model can help inform.

NEW OPPORTUNITIES FOR PRACTICE-BASED INCENTIVES

Implementation of carbon-enhancing silviculture across northern Maine's landscape will require innovative policy thinking to ensure more carbon is sequestered without reducing harvests. The FCCL team suggests that, in addition to ongoing initiatives to improve forest offset markets, efforts to develop incentives should focus on how expanded use of practice-based programs might be used to implement "carbon-smart" forestry that is truly additional and non-leaking.

Photo by Twolined Studio

NEXT STEPS

Overall the FCCL study should be viewed as a promising proof of concept—that Maine's commercial timberland owners could be incentivized at competitive costs to sequester more carbon across the landscape and in HWPs. But the FCCL work, while integrating a wealth of detail about silvicultural systems and forest economics, still relies on numerous simplifying assumptions that result in important uncertainties needing further exploration as part of the policy development process. Because some of the alternative silvicultural systems proposed have not been widely implemented, practiced, and studied at scale and over time on lands managed with a history of more conventional silvicultural systems, one initial goal would be to broaden the establishment of demonstration and study areas under programs like the Cooperative Forest Research Unit's Maine Adaptive Silviculture Network. Additional work with landowners is also needed to validate the results of the FCCL modeling at finer scales. In particular, there is a need (1) to demonstrate that harvests and net revenues can be maintained over shorter time scales and (2) to refine the carbon and product modeling for uneven-aged and plantation silvicultural systems through scenarios that include increased production of and demand for durable wood products. At the same time, stakeholder coalitions could be assembled to begin more detailed discussion about incentive design and implementation. For example, under the $30 million USDA Climate Smart Commodities grant recently awarded to the New England Forestry Foundation, pilot projects could test the effectiveness of incentive-based programs for promoting carbon-smart silvicultural practices. The FCCL study identifies important considerations, asks key questions, and lays initial groundwork for embarking on these processes. Support for these activities from the State of Maine could be instrumental in making carbon-smart forestry a reality.

01

INTRODUCTION

The growing emphasis on achieving net zero fossil fuel emissions by mid-century is shining a spotlight on natural climate solutions in the forestry and agricultural sectors (Joppa et al. 2021). Many corporations and other greenhouse gas (GHG) emitters, searching for ways to fulfill their net zero pledges, must find cost-effective alternatives for mitigating emissions that are either prohibitively expensive or technically challenging to eliminate.

In this context, natural climate solutions that remove CO_2 from the atmosphere and store it in the biosphere have great appeal.[1] In the forestry sector over the past several decades, the U.S. has seen the development of both regulated (compliance) and voluntary markets for forest carbon "offsets" designed to meet this need (van der Gaast et al. 2018). Conceptually, these offset programs pay forest landowners to adopt new management practices that sequester and store more carbon going forward than their baseline business-as-usual (BAU) practices. Following verification, landowners can then sell carbon offset credits to GHG emitters who want to offset fossil fuel emissions that are difficult or expensive to eliminate. In the U.S., the cost of offsetting the equivalent of a metric ton of CO_2 emissions through forest offsets has recently exceeded $25/tCO2e in the California compliance market (CarbonCredits.Com, n.d.). Historically, prices have been far lower in voluntary markets (Ecosystem Marketplace, n.d.), although anecdotal information suggests both prices and demand for voluntary offsets have risen significantly in 2022. For comparison, potential industrial-scale technologies that remove carbon directly from the atmosphere and permanently store it in geological formations currently cost hundreds of dollars per ton of CO_2 (Joppa et al. 2021). The economic appeal of low-cost natural climate solutions is obvious.

Recent critiques of forest carbon offset protocols, however, point to certain problems that can compromise their effectiveness in combating climate change (Elgin 2022, Temple and Song 2021). Principally, these fall into three categories—additionality, leakage, and permanence. This paper discusses the first two. Unless

1 Natural climate solutions are land stewardship activities that can remove and store carbon from the atmosphere. Improved forest management is an example. The potential for these types of climate solutions has been discussed by Griscom et al. (2017).

Photo by Lauren Owens Lambert

addressed, these issues will continue to undermine the legitimacy of many forestry-based natural climate solutions. Permanence for forestry projects is not addressed here but could be achieved by repeated application of the silviculture described in this report.

BACKGROUND TO THE STUDY

In August 2020, a small group of forest landowners, scientists, philanthropists, conservationists, and others—calling themselves the Forest Carbon for Commercial Landowners (FCCL) Initiative—began meeting monthly to explore the following questions:

> *Can large commercial forest landowners in northern Maine store more carbon in the forest and in forest products while maintaining harvest levels?*
>
> *And, if this could be done, how might the needed changes in landowner behavior be incentivized?*

If stores of carbon in the forest and in products could be increased by carbon-enhancing silvicultural practices without reducing current harvest levels, the issues of both leakage and additionality would be addressed. Moreover, we would avoid negatively affecting forest-based communities that depend on wood harvesting, and potentially even grow the forest economy through the production of more and higher-quality timber.

Not presuming to know the answer to the first question, the FCCL group set out on a fact-finding mission. A series of presentations and discussions ensued through the fall of 2020. By year's end, the group concluded that a more structured and thorough analysis would be required to answer these questions.

WHY DOES THIS WORK MATTER?

Increasingly, the adoption of net zero policies, both by corporations and other entities like individual states, creates both opportunities and challenges for the development of "climate-smart" approaches to managing timberlands in Maine. The state has a very high proportion of timberlands—roughly 89 percent is forested—potentially creating valuable opportunities for forest landowners to benefit from policies that incentivize sequestration of carbon in the forest and in forest products. Some 10 million acres of forest are owned by large commercial entities. These timberlands are managed for multiple purposes, but with a strong focus on investment performance.[2] Moreover, Maine has established a target of

2 Many landowners in the region manage in compliance with forestry indicators and criteria established under the Forest Stewardship Council and/or Sustainable Forestry Initiative standards, with an estimated 18 percent of their acres in actual unharvested set-asides or special management areas with limits on harvest (such as riparian buffers).

achieving carbon neutrality (net zero) by 2045, and forest carbon policies could help the state achieve this goal.[3]

This creates a situation where northern Maine's commercial forest owners can potentially play a meaningful, science-based role in mitigating climate change if they can increase the amount of carbon sequestration and storage in wood products harvested from these lands. The forests on these lands already sequester and store large amounts of carbon each year. The work described in this report, which focused on a 7.6-million-acre northern Maine study area, projects that under current management standards these lands, net of harvests, growth, and decay, will sequester and store a minimum of 3.6 MtCO2e per year on average over the next 60 years. This includes 1.6 MtCO2e per year in long-lived harvested wood products (HWPs). The FCCL study has intentionally focused on these commercial forest lands because of economies of scale, and because, at the time the FCCL initiative began, the existing carbon markets, designed to provide incentives for increased carbon sequestration, had only enrolled about 3.5 percent of Maine's commercial forest land base (Truesdale 2020).[4]

The challenges to increasing forest carbon come in finding approaches meeting the conditions needed to ensure that any increases result in real reductions in carbon in the atmosphere—reductions that are additional, non-leaking, and permanent.[5] Deferring timber harvests to store more carbon in the forest is being promoted as a carbon storage strategy by some (Securing Northeast Forest Carbon Program, n.d.). With respect to the atmosphere, however, this strategy is questionable if deferred harvests are simply shifted to another part of the region or globe—this is the leakage issue. Also, some projects under existing improved forest management (IFM) offset protocols (voluntary and compliance) may be paying for forest management that would have happened anyway. Critics have pointed to cases where offsets have been purchased that in all likelihood did not lead to reductions in atmospheric GHG levels relative to the continuation of business as usual by the landowner—this is the additionality issue. Finally, when working with forests, there are always questions about the permanence of the carbon offsets. At some point in the future, trees will either be harvested or eventually die, and their carbon will be returned to the atmosphere. How to account for the temporal aspects of forest offsets across the landscape is an ongoing topic of discussion—the permanence issue (Chay et al. 2022).[6]

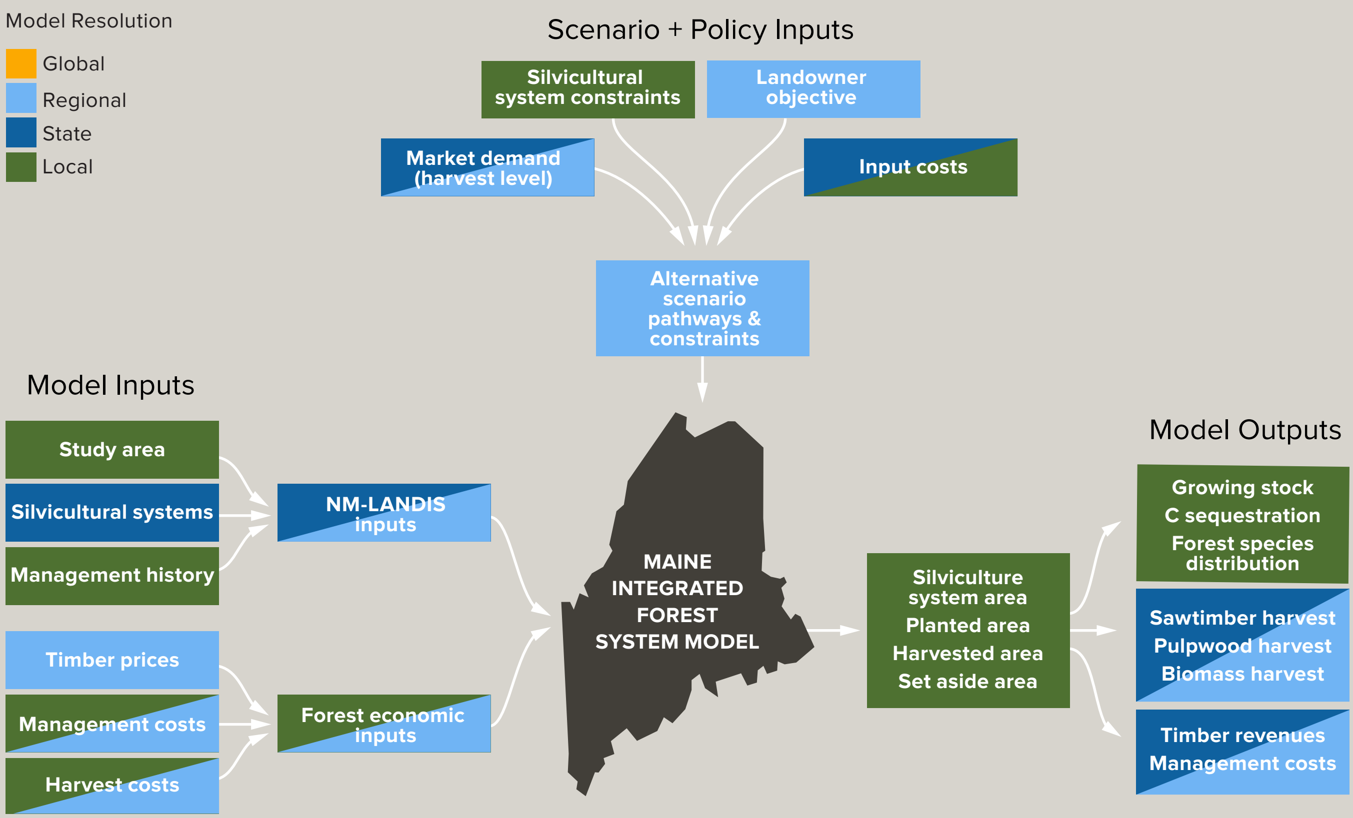
3 Use of additional carbon to meet the state's net zero goals raises potential "double-counting" issues that are beyond the scope of this report. These issues would need to be addressed in the development of incentive instruments designed to promote implementation of the types of non-leaking silvicultural systems discussed in this report.

4 Recent anecdotal information and data from carbon offset registries suggests Maine landowners are showing increased interest in potential offset sales, perhaps due to recently reported price increases.

5 For forest offset protocols, permanence has typically been defined as a commitment to store carbon for 100 years. Where this is the case, the biosphere constitutes a form of temporary rather than permanent storage in comparison with methods such as sequestration in geologic formations. But even so, there is potential value in such extended but ultimately temporary deferrals of emissions given the possibility that technological progress ultimately provides more permanent and lower-cost solutions not available today.

6 Of course, trees can be regrown and silvicultural systems can provide a steady supply with management. An easement could ensure permanence.

FIGURE 01. Overview of Modeling Framework



To evaluate these opportunities and challenges, we need to identify the attributes of carbon-smart approaches to forest management that lead to real, verifiable reductions in GHGs. To realize this opportunity, Maine's landowners and policy makers need a robust understanding of whether and under what conditions landowners can profitably manage their forests to accelerate carbon sequestration that is truly additional, non-leaking, and permanent.

THE FCCL HYPOTHESIS AND MODEL

This study reports the results of a bio-economic modeling analysis of forestry practices with the potential to enhance carbon sequestration and storage on 7.6 million acres of forest land in northern Maine. The foundation for the study is the identification of changes to silvicultural practices that, if implemented, could lead to an increase over time of carbon stored in the forest and in HWPs relative to the continuation of current forestry practices in Maine. The silvicultural alternatives would result in carbon additionality because the incremental carbon would not have been sequestered under a business-as-usual scenario. Under each of the silvicultural systems selected for analysis, average biomass harvested was held constant over the 60-year timeframe for the study (2010–2070)—at levels designed to reflect current harvests—to support Maine's forest products industry and minimize potential leakage.

The biological development of the forest, both in the baseline and silvicultural alternatives, is projected using LANDIS-II, a landscape-scale forest modeling tool (Simons-Legaard, Legaard, and Weiskittel 2021). Output from LANDIS serves as input to the Maine Integrated Forest System Model (MIFSM), an economic optimization tool that can evaluate the potential carbon, timber, and landowner financial impacts of applying different silvicultural practices for a range of forest types and stand conditions. The structure of the model is flexible and can be used to evaluate various alternative objectives (carbon, cash flow, etc.) subject to a range of constraints (harvest levels, spatial area devoted to different silvicultural systems, etc.). This framework allows evaluation of the relative impacts over time of alternative silvicultural systems and incentive policies on carbon, harvests, and measures of landowner financial returns.

For the FCCL study, the potential for increased use of silvicultural approaches that sequester more carbon is considered for three scenarios that illustrate the effect of policies that would incentivize carbon-smart practices. These scenarios illustrate the impacts of (1) increasing uneven-aged forest management; (2) the effects of expanding plantation-style management accompanied by an increase in unharvested areas over our 60-year time frame; and (3) a theoretical upper limit on the impacts of applying silviculture to increase forest carbon. For all three scenarios, we provide estimates of the levels of incentives that would be required to get landowners to adopt the alternative silvicultural systems and the amount of additional carbon that would be sequestered by the scenarios. Incentives could take the form of traditional payments for carbon offsets or they could be made in the form of direct payments for adoption of specific silvicultural practices. These incentives also have the potential to maintain the many other values provided by Maine's forests, from wildlife habitat and watershed health to the forest products and outdoor recreational economies.

Photo by Lauren Owens Lambert

REPORT ORGANIZATION

The remainder of the report is organized into the following major sections.

02

SELECTION OF SILVICULTURAL SYSTEMS FOR POLICY MODELING

We conducted a review of the scientific literature and consulted with silvicultural experts to select a portfolio of silvicultural systems that might sequester and store more carbon in forests and store more carbon in HWPs. The literature review revealed the following key insights regarding the potential for silviculture to increase carbon sequestration and storage.[7]

First, it is difficult to glean from the literature robust and generalizable quantitative estimates of the impact of different silvicultural systems on carbon sequestration and storage in HWPs. The problem is that factors such as initial stand conditions, harvest quantities, treatment timing, and frequency vary considerably across studies, making it challenging to directly compare results. Moreover, there are too few studies to develop robust, statistically controlled estimates of cross-practice impacts. Finally, much of the literature for our region focuses on stand-level impacts and, as will be clear from the analysis presented in this study, application of silviculture at the stand level has important landscape-scale interactions that need to be considered holistically to quantify changes to carbon sequestration and storage.

Nonetheless, the literature review does provide some high-level insights about the effectiveness of silvicultural systems at sequestering and storing carbon. Over the long haul, the studies make clear that for a fixed timeframe (and not factoring in leakage or catastrophic events), unmanaged and unharvested stands will cumulatively sequester and store more total ecosystem carbon than harvested stands, even when HWPs are included. This has caused researchers to recommend the incorporation of unharvested reserves in forest management plans if increasing carbon storage is an objective (Granstrom 2019, Gunn and Buchholz 2018, Mika and Keeton 2015, Nunery and Keeton 2010), noting, though, that care must be taken when reducing forest harvesting capacity in certain portions of the landscape to prevent leakage that would result from increasing harvesting elsewhere (Daigneault et al. 2021). At the stand level, however, the rate of carbon

7 For more details on the literature review, see the more detailed spreadsheet linked in Appendix A.

Photo by Kari Post

sequestration will diminish as carbon storage increases, and older stands can be adversely affected by climate change and catastrophic events. Younger stands typically sequester more carbon as they are growing at a relatively fast rate, and active management helps regulate species composition and stocking, driving growth. In our model, with a prescribed harvest level over the study period, if we increase sequestration, we will also increase carbon storage at the landscape scale.

Researchers also have observed that certain forest management practices can balance meaningful carbon sequestration with the provision of other forest ecosystem services, including the ability to harvest timber. This was noted by Puhlick et al. (2020) relative to the commonly used baseline practice of fixed-diameter-limit harvesting, which did not appear to sequester and store as much carbon as other management approaches. Other studies suggested that shifts from even- to uneven-aged stand structure (Gunn and Buchholz 2018) and increased structural complexity (Ford and Keeton 2017) were associated with greater carbon stocks (while also improving timber quality), although sequestration was not addressed. All studies that considered clearcut harvests followed by natural regeneration found that this approach stored less carbon than stands undergoing other less intensive treatments (Granstrom 2019, Puhlick et al. 2016a), although artificial regeneration following clearcutting may contribute to increased carbon sequestration and storage when incorporated into a landscape-scale plan that includes not harvesting older forested lands (Daigneault et al. 2021).

Selection silviculture was shown repeatedly to favor carbon storage as compared with business as usual (Granstrom 2019, Puhlick et al. 2016a, Puhlick et al. 2016b), as was decreased harvesting frequency and retention of greater residual basal area (Gunn and Buchholz 2018, Nunery and Keeton 2010, Valipour et al. 2021). Harvesting for wood energy has been more controversial but can have beneficial net carbon impacts depending on factors such as the specific source of the biomass fuel, the fossil fuel being replaced, the energy system technology, baseline assumptions about what would have happened to the biomass in the absence of burning for energy, and the timeframe considered in the analysis (Gunn and Buchholz

Photo by Carrie Annand

2018). Finally, Cameron et al. (2013) looked at the role of forest management in a full GHG life-cycle analysis for a large integrated forest products company and concluded that "intensive forest management to produce a sustainable long-term supply of solid wood products and bio-fuel may result in a GHG mitigation potential similar to that when forests are allowed to grow unmanaged, while providing forest products that produce societal benefits."

In summary, the available literature has focused predominantly on carbon at the stand level. But at a landscape scale, managing to increase carbon is a dynamic process that must consider many stands and their management simultaneously. As the modeling in this report will suggest, over time the level of increased carbon benefits to the atmosphere from forest management is a function of both the carbon stand dynamics of the silvicultural systems applied and the proportions of the landscape allocated to (1) stands actively managed for timber and (2) stands that are unharvested at any point in time.

Based on these insights and others gathered from conversations with silvicultural experts, we describe seven simplified land management practices for inclusion in the modeling analyses described in this report.[8] These are summarized below in Table 1.

1. **Partial Harvest:** A moderate harvest option removing 50 percent of stand biomass but with no explicit stand regeneration objectives.[9] The remaining 50 percent is eligible to be harvested 50 years later, along with any new growth.

2. **Clearcut with Natural Regeneration:** Initial removal of 100 percent of standing timber volume. Regeneration relies completely on natural regrowth. No additional site preparation or removal of competing or undesirable species is conducted. This results in an even-aged stand that is expected to be ready for harvest at year 50.

8 "Partial harvest" and "unharvested areas" are not referred to as silvicultural systems in the terminology used for this report since they do not include explicit silvicultural objectives.

9 From a modeling perspective, this is implemented as a nonselective harvest in which 50 percent of the biomass is removed with no preference for species or quality. The treatments other than partial harvest implement silvicultural activities that target more defined objectives such as increased timber quality or higher growth and yield.

3. **Clearcut and Plant:** Initial removal of 100 percent of standing timber volume. Regeneration relies on planting. Competition from undesirable species is typically managed with herbicides but can be managed with mechanical treatment.[10] Commercial thinning at year 25. This results in an even-aged stand that is expected to be ready for harvest at year 50.[11, 12]

4. **Regular Shelterwood:** Initial establishment cut removing 60 percent standing timber volume followed at year 10 by removal of remaining overstory. Pre-commercial thinning (PCT) at year 25. Commercial thinning at year 40. Results in an even-aged stand with a new cycle beginning with an establishment cut in year 60.

Photo by Kari Post

5. **Irregular Gap:** Small gaps with 100 percent removal created in thinned forest matrix on a 20-year cycle. Gaps thinned on a 20-year cycle after creation. Commercial thinning from below outside the gaps. Results in uneven-aged (multi-aged) stands that are continuously harvested.

6. **Continuous Cover:** Commercial thinning/establishment cuts repeated at 30-year intervals with 35 percent of the standing volume removed. Results in uneven-aged (multi-aged) stands continuously harvested.

7. **Unharvested Areas:** In unharvested areas, the forest sequesters carbon subject to ongoing natural growth and disturbance processes.

Using the land management practices described above, we constructed a baseline—often referred to as a business-as-usual (BAU) scenario—against which we compare scenarios that alter the mix of silvicultural systems to increase carbon sequestration (and potentially storage in HWPs).[13] The BAU scenario comprises the practices most widely used today in northern Maine. They are applied across the study area in the BAU at rates that allow the continuation of current

10 While it can be done mechanically, this would be at greater expense and this scenario has not been modeled for this study.

11 Although not included in our modeling scenarios, some current timberland managers expect to be able to harvest after 35 years on some sites.

12 The clearcut and plant scenario for this report assumes spruce plantations. White pine plantations, however, are also a real possibility in Maine. White pine is a fast-growing softwood species and would be a good contributor from a carbon sequestration perspective. J.D. Irving, Ltd., has been establishing white pine plantations in the region in a number of contexts, including as species mixtures, for over 20 years. In the past year it produced over 500,000 seedlings—a number that is increasing. While growing white pine is not without its management challenges, there are options that can result in very high quality, fast-growing white pine.

13 The primary scenarios (1–3) discussed in the main body of this report hold harvests constant and assume a fixed 60/40 ratio of pulp to sawlogs. As a result, while our total carbon estimates include carbon in HWPs, the estimates of additional carbon in these scenarios reflect only additional sequestration in the forest because product outputs do not change. The overall quantity and profile of harvested products is not changed. These assumptions are relaxed in the Technology Innovation Scenario discussed in Appendix C.

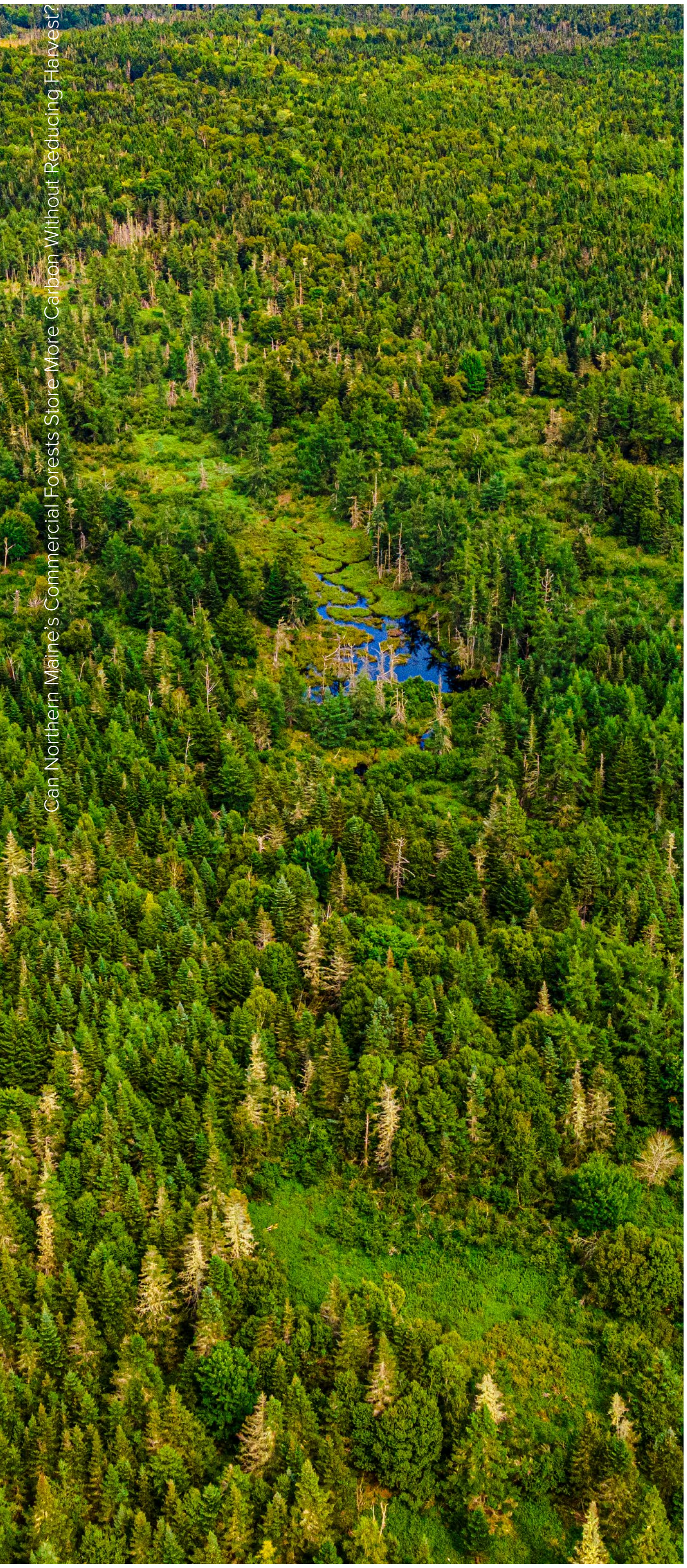


Photo by Michael Perlman

annual harvests (2 million tons of carbon per year (MtC/y) or approximately 7.3 million tons of CO_2e per year ($MtCO_2e/y$)) over the 60-year study horizon. This results in the allocation of 50 percent of the study area to partial harvests, 19 percent to regular shelterwood, 10 percent to clearcuts with natural regeneration, and 3 percent to clearcuts that are planted, leaving 18 percent of the acreage unharvested, either because it is in land that is functionally set aside in reserves (e.g., stream corridors, deeryards or currently protected areas) or because it is not needed to meet current harvest goals during the model's time horizon.[14]

Finally, as a point of reference, we also analyzed the impacts from a carbon perspective of not harvesting any timber and just allowing the forest to grow. The LANDIS-II modeling projects that over our 7.6-million-acre study area, forests sequester approximately 8.7 $MtCO_2e/y$.[15] This represents maximum average annual sequestration if all harvesting activities ceased for 60 years but does not consider the prospect of catastrophic events. Relative to the continuation of current trends, this constitutes more than doubling of sequestration.

But the "let it grow" scenario's apparent carbon benefits do not result in the same level of net climate benefits. In a global economy—one generally characterized by rising populations and an increasing appetite for lumber, paper, and other forest products—demand for forest products would not be reduced significantly by a cessation of harvesting in Maine. Carbon sequestered under a no-harvest scenario in northern Maine therefore would not be additional; the timber that would otherwise be cut in a baseline scenario would instead be harvested in locations either elsewhere in Maine, in other regions of the U.S., or around the globe, thus negating the climate benefits of additional sequestration in northern Maine. This form of leakage over the time period used for our analysis is highly likely given the efficiency of forest product markets (Pan et al. 2020). Moreover, without providing any climate benefits, applying a let-it-grow strategy broadly across northern Maine would starve the state's forest products economy of necessary inputs and undermine the health of forest-dependent communities in the region. As a

14 Continuous cover and irregular gap are not widely practiced at present on commercial lands in northern Maine and therefore are not included in the BAU.

15 Output for the LANDIS-II simulations for the let-it-grow scenario can be viewed at https://umaine.edu/forestpolicy/models-and-data/.

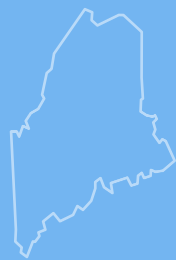
TABLE 01. Silvicultural Practices Modeled

	SYSTEM						
	Partial Harvest	**Continuous Cover**	**Regular Shelterwood**	**Irregular Gap**	**Clear Cut Plant**	**Clear Cut Natural**	**No Harvest**
Description	Non-system moderate harvest, non-selective	Continuous cover irregular shelterwood	Regular shelterwood, typical rotation	Gap irregular shelterwood	Clearcut, plant native	Clearcut, natural regeneration	No harvest / Reserve
Treatment 1	Harvest @yr 0, 50% removal	CT/Estab. Cut @yr 0, 35% removal	Estab. Cut @yr 0, 60% removal	CT/Harvest Gaps @yr 0, 100% removal gaps (20% of area), 20% removal matrix, combined low and crown thinning	100% removal @yr 0, herbicide, spruce	100% removal @yr 0, naturally regenerate	—
Treatment 2	Harvest @yr 50, 50% removal	CT/Estab. Cut @yr 30, 35% removal	OSR @yr 10, 100% removal	PCT in gaps @year 15	CT @yr 25, 35% removal	100% removal @yr 50, naturally regenerate	—
Treatment 3	—	100% removal @yr 50, naturally regenerate	PCT @yr 25, favoring spruce	CT/Harvest Gaps @yr 20, 100% removal gaps (20% of area)	100% removal @yr 50, herbicide, plant spruce	100% removal @yr 50, naturally regenerate	—
Treatment 4	—	—	CT @yr 40, 35% removal	PCT or CT in gaps @year 35, 35% removal,	—	—	—
Treatment 5	—	—	Estab. Cut @yr 60, 60% removal, prioritizing fir	CT/Harvest Gaps @yr 40, 100% removal gaps (20% of area)	—	—	—
Treatment 6	—	—	—	PCT or CT in gaps @year 55, 35% removal,	—	—	—
Treatment 7	—	—	—	CT/Harvest Gaps @yr 60, 100% removal gaps (20% of area)	—	—	—

reference point, however, the let-it-grow scenario provides an upper bound on the carbon sequestration potential of the forests in the FCCL study area if left to grow unmanaged and assuming no future negative impacts on carbon sequestration from climate change itself.

For each practice, the detailed stand entry and treatment assumptions used in the LANDIS-II model are summarized in Table 1. As discussed further in the next section, more detailed stand entry and management prescriptions were developed for individual forest types in LANDIS. These are available for review at https://umaine.edu/forestpolicy/models-and-data/.

03



FOREST AND POLICY MODELING APPROACHES AND TOOLS

The FCCL modeling uses an integrated approach that links estimates from a forest landscape model (LANDIS-II) with economic and policy data and assumptions into a linear programming optimization framework (MIFSM) to quantify the potential impacts of employing various silvicultural treatments across commercial forestland in northern Maine. This section provides an overview of the two models and how they were integrated to conduct the FCCL study.[16]

LANDIS-II

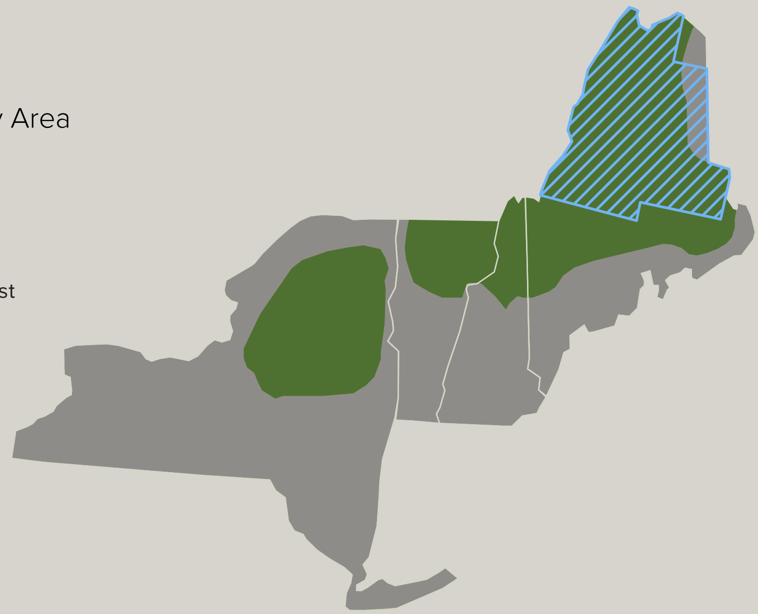
Overview of LANDIS-II Model Implementation for FCCL

LANDIS-II is a widely used forest landscape modeling tool for projecting broad-scale effects of human and natural disturbances. Within LANDIS-II, the forest is represented by a grid of interacting cells, aggregated by user-defined ecoregions (homogeneous soils and climate). Cells were 30 x 30 meters in this study. Forest succession processes, including tree establishment, growth, competition, and mortality, are modeled based on empirical 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. Each cell can contain multiple cohorts, and initial forest conditions are generally provided by, for example, land cover or forest type maps, and FIA data on subordinate cohorts likely given the overstory. Cells are linked by the processes of seed dispersal, natural disturbance, and land use. 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.

For this study we used a customized version of LANDIS-II previously developed by Simons-Legaard et al. (2021) to model the effects of alternative silvicultural

16 For more information on the use of LANDIS-II and MIFSM for this study, please refer to the background report prepared by researchers at the University of Maine and USDA Forest Service in Appendix C: *Data and Modeling Details for the Forest Carbon for Commercial Landowners Project* (2022), prepared for the FCCL Project by Adam Daigneault, Erin Simons-Legaard, Jeanette Allogio, Laura Kenefic, Aaron Weiskittel, Zoë Lidstrom.

FIGURE 02. FCCL Model Study Area



treatment strategies on the carbon and harvest dynamics of approximately 7.6 million acres of forested area in northern Maine. Results tracked impacts to Maine's 13 most abundant tree species, which accounted for 86 percent of Maine's aboveground forest biomass as of 2010. Initial forest conditions were provided by maps of tree species' relative abundance developed for our study area using USFS FIA plot data and Landsat satellite imagery.[17] Our study area (Figure 2) encompasses a total of approximately 9 million acres, of which 7.6 million acres are forest land. Timberland within this area is predominantly held by large landowners (>10,000 acres) and represents a diverse range of ownership types (e.g., family, high-net-worth individuals, timber investment management organizations, real estate investment trusts, and nonprofit organizations).

The LANDIS-II simulations project changes in forest biomass over the 60-year period from 2010 to 2070.[18] We used the biomass projections to estimate standing carbon in the forest and in HWPs by decade. Through comparison with the BAU baseline scenario, we estimated whether additional carbon could be sequestered and stored by moving to a landscape characterized by greater use of our alternative silvicultural systems, and if so, how much. Various versions of LANDIS-II have been applied to the Northern Forest region (Thompson et al. 2011; Simons-Legaard, Legaard, and Weiskittel 2021; Duveneck and Thompson 2019; Graham MacLean et al. 2021). Since its release, LANDIS or the updated version LANDIS-II have been used in more than 100 peer-reviewed publications to simulate the impacts of a wide variety of disturbances for which model extensions have been developed (Legaard, Simons-Legaard, and Weiskittel 2020).[19]

17 Following the methods of Legaard, Simons-Legaard, and Weiskittel (2020).

18 While the LANDIS results are based on the period from 2010 to 2070, for the purposes of our study they provide an approximate indication of the impacts of alternative silvicultural practices if they were implemented in northern Maine over 60 years beginning today.

19 The model calibrated the Base Wind extension to simulate a 0.1 percent rate of annual area disturbed by small to moderate wind events (Lorimer 1977; Lorimer and White 2003; Seymour, White, and deMaynadier 2002). "Stands" eligible to be cut in the Biomass Harvest extension had a minimum mapping unit of nine cells, or approximately one hectare. Our LANDIS-II modeling did not explicitly account for other disturbances, such as spruce budworm infestations, fires, other insects and diseases, etc.

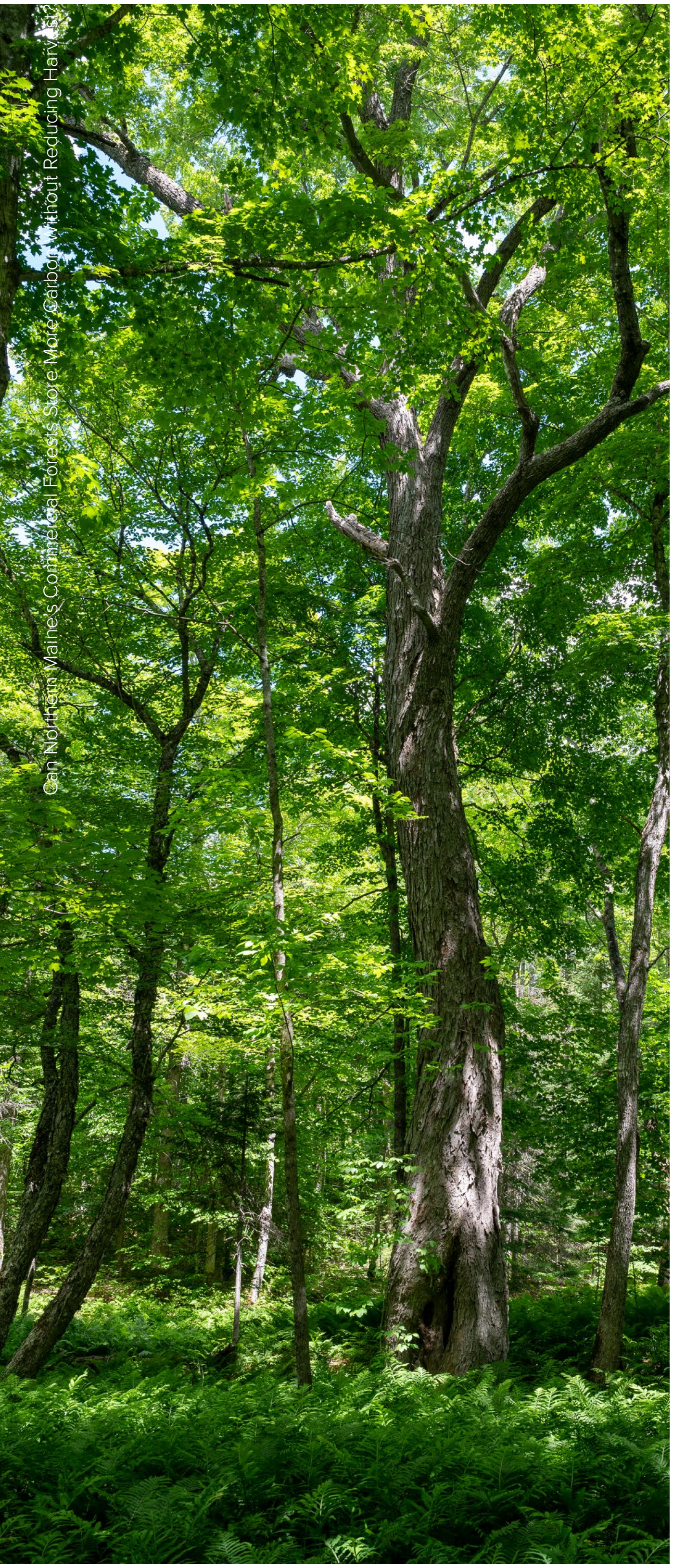


Photo by Twolined Studio

Advantages and Limitations of LANDIS-II

LANDIS-II was selected for this study due to its ability to model the ecological dynamics of forest carbon at a very wide spatial scale. This allows us to address the leakage issue at a regional scale. In addition, LANDIS-II had already been parameterized and calibrated for the Acadian forest (Simons-Legaard, Legaard, and Weiskittel 2021). A previous study used LANDIS-II for similar investigations of the carbon potential of a more limited set of silvicultural practices on Maine's timberlands (Daigneault et al. 2021).

LANDIS-II, however, has two fundamental limitations as a tool for the FCCL modeling effort. First, it is limited in its ability to model more complex silvicultural treatments that rely on the application of many different treatments to the same stand, particularly when including different approaches to thinning (low, dominant, crown). Additionally, LANDIS-II does not recognize individual trees but rather cohorts of trees within each cell. It is therefore challenging to make comparisons between silvicultural systems that use different approaches to selecting individual trees for thinning to stimulate different aggregate growth responses in a stand, or that yield different mixes of pulp and sawlogs. For this study we were able to adapt LANDIS-II to provide a general approach to thinning based on the age of tree cohorts that reduced the overall amount of biomass in a stand, which we used as part of the continuous cover and irregular gap silvicultural systems included in our study. This was calibrated based on the expert judgment of the FCCL silvicultural team. More nuanced silviculture including removals based on, for example, tree position in the stand or quality of the trees removed (or the species) was not possible.[20] Our analysis would benefit from further work in this area.

Second, because LANDIS-II provides results in terms of biomass by species or age class for each 30 x 30-meter cell, it cannot be used to explicitly project the mix of merchantable products that silvicultural systems could produce. Following through on the thinning example, two stands may have the same biomass some years after thinning but this could be concentrated in a very different number of stems per acre, and hence in a different proportion of sawlogs versus pulp. LANDIS does not provide

20 Appendix B is a brief summary by Dr. Aaron Weiskittel on impacts of pre-commercial and early commercial thinning with reference to carbon sequestration.

individual tree information that allows a determination of how much of the biomass is merchantable sawlog versus pulpwood or studwood. Instead, this must be based on externally derived assumptions. This is a significant shortcoming because the production of greater amounts of sawlogs has a direct impact on carbon sequestration. To address this limitation, we applied externally generated estimates of the expected product mixes for the various cohort ages. But we are unable to confirm that these results are fully consistent with the biological modeling from LANDIS-II. The results would be more compelling if the modeling directly produced estimates of biomass by tree size instead of age.

Nonetheless, the advantages of LANDIS in being able to simultaneously model species growth and succession dynamics at a fine scale across a broad landscape, while also accounting for species succession/change under a broad range of conditions, make it a useful tool for highlighting the trade-offs of implementing different management options (simultaneously) across a broad area. Models like FVS, while they have other benefits (e.g., information on individual trees in terms of diameter, condition, and likely products) are not designed to predict likely regeneration after harvest or to take geographically specific interactions between stands into account or to model random events. The benefits of integrating LANDIS and the MIFSM model are discussed further in the next section.

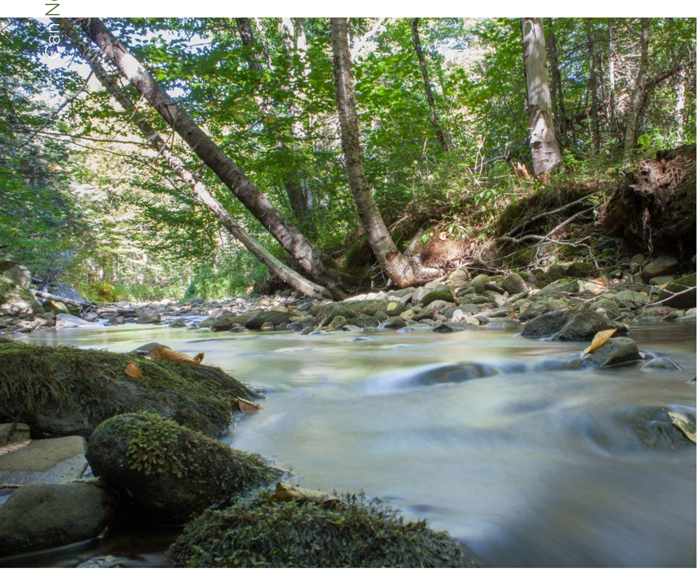


Photo by Charlie Reinertsen

MAINE INTEGRATED FOREST SYSTEM MODEL

Model Overview

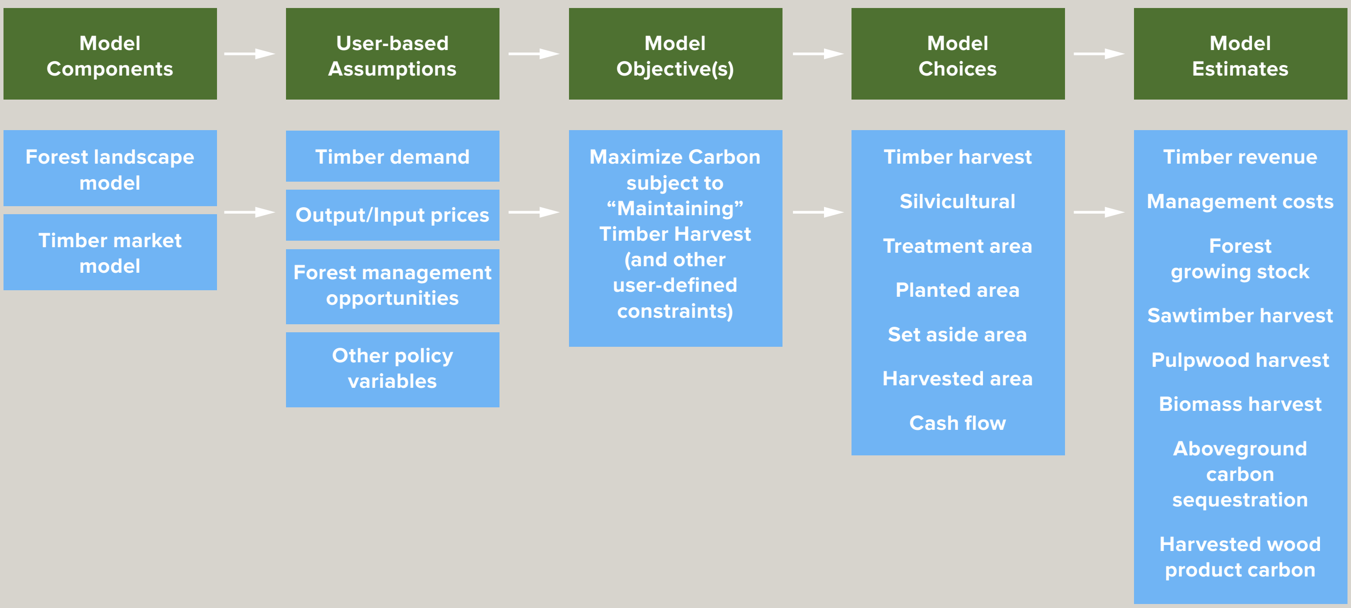
The Maine Integrated Forest System Model (MIFSM) has been developed to systematically evaluate potential impacts from implementing different forest management options across Maine's working forests. The decision support tool links a series of models related to forest growth and harvesting to quantify the economic and environmental benefits and costs of different silvicultural practices under alternative policy scenarios, thereby allowing a better understanding the various trade-offs that could emerge.

MIFSM's flexible optimization approach can be used, for example, to ask questions such as:

- What mix of alternative management practices would maximize carbon sequestration and storage on Maine's commercial timberlands?
- How might the choice of silvicultural practices change if the goal were to maximize carbon without reducing timber harvests over a given time period?
- What levels of carbon payments or practice-based incentives would be required for landowners to find it economically feasible to adopt these alternative management practices?

For this project MIFSM evaluates the 108 unique forest type combinations that vary in species, site productivity, and initial stand conditions to represent the 7.6 million acres in our study area and selects the optimal mix of practices and harvest schedules to employ across the landscape to meet a specified objective (e.g., maximizing carbon while holding harvests constant). As part of the FCCL research agenda, the model was updated with growth, yield, and harvest estimates from LANDIS-II.

FIGURE 03. General MIFSM Model Framework



In the general MIFSM model framework, LANDIS-II represents the forest landscape model while the economic data represents the timber market model (Figure 3).

The model includes a harvest constraint to ensure that forest removals are held constant at the target level (i.e., 7.3 MtCO2e/y). Additional constraints allow further specification of underlying pulp and sawlog targets (approx. 60/40 of total harvests) to ensure that a balanced mix of products are harvested.[21]

21 For the three primary scenarios, we assume harvests are approximately a 60/40 mix of pulp to sawlogs. A log is assumed to be a pulp log if it is from a tree up to 40 years old. All trees older than 40 years are assumed to produce sawlogs. This is consistent with the Maine Forest Service and FIA removal data (see Appendix C). These assumptions could be modified in MIFSM to explore the impact of silviculture on the production of more (or less) sawtimber over time.

Spruce regeneration in thinned stand
Photo by Maine Forest Service

The input to MIFSM from LANDIS tracks the in-forest carbon pools and includes aboveground live (AGL) biomass and harvested biomass based on growth, yield, and harvest information that is empirically derived (see Appendix C). MIFSM converts the harvested biomass to products and estimates the average portion of pulp and sawlog carbon that remains in storage over 100 years. Total sequestration and storage is the sum of net decadal sequestration in the AGL pool summed across the six modeled decades plus the carbon in long-term HWP storage.

Constraints are also available to specify the amount (acreage) of a silvicultural practice that can be employed, which can be varied by scenario. These constraints include the amount of land that can be allocated to unharvested areas, clearcut, or implemented as one of the other five silvicultural practices.

The MIFSM model solves the given optimization problem subject to a mix of the constraints described above by allocating the area of each of the 108 forest type combinations across the seven possible silvicultural treatments specified in Table 1. The optimal mix of treatments can vary by scenario depending on the specifics of how much land is allowed to be allocated to different practices as well as the relative carbon and net annual revenue values of each possible combination. To parameterize MIFSM, we use LANDIS-II results to estimate sequestration, harvest levels and net revenues that have been averaged over the 60-year modeling period for each of the 108 forest types rather than the individual shorter-term decadal values directly from LANDIS. This was done to smooth out variability around the 7.3 MtCO2e harvest target in the LANDIS-II decadal results.[22] This averaging approach has important limitations with respect to development of finer scale (decade-by-decade) estimates of carbon, harvest, and net revenue dynamics. These limitations and their implications are discussed in Section 5.

22 LANDIS is an acreage-based rather than a volume-based model and this is the source of the variability of harvest volumes around the 7.3 MtCO2e/y. Averaging allows harvests to be constrained more directly based on volumes in MIFSM.

04

ALTERNATIVE SILVICULTURE SCENARIOS

For this study, we developed modeling scenarios that focused on the continuation of current trends in the forest products sector to assess the impacts on carbon sequestration of implementing alternative mixes of silvicultural systems across our 7.6-million-acre northern Maine study area.[23] Initial investigations using LANDIS-II and MIFSM suggested that, generally, silviculture can increase carbon sequestration through implementation of silvicultural systems that (1) invest in practices that increase production and harvest from smaller areas (e.g., even-aged systems such as clearcut-and-plant systems) or (2) promote practices that manage and harvest less intensively but more selectively across a wider area (e.g., uneven-aged management systems such as continuous cover and irregular gap). To illustrate the landscape dynamics and impact of these key drivers of forest carbon, we developed three scenarios for comparison with the BAU baseline scenario described above in Section 2.

Uneven-aged stand
Photo by Kari Post

- **Scenario 1—Expanding Uneven-Aged Silviculture:** This scenario illustrates the potential opportunities for silviculture to increase carbon sequestration over 60 years without dramatic changes in the proportion of the landscape currently devoted to plantation silviculture. Scenario 1 generally adopts the assumptions of the BAU scenario but uses the model to maximize annual carbon sequestration instead of average annual net revenues. This scenario illustrates how the study-area acreage allocated to the various silvicultural systems would change relative to the BAU scenario if increasing carbon is the goal. It also estimates the additional costs that landowners would incur to implement silviculture that enhances carbon sequestration given the requirement to meet the 7.3 MtCO2e/y harvest target and land use constraints similar to those in effect

23 Under Scenarios 1 through 3, because the mix of pulp and sawlogs is held constant at the 60/40 ratio, there are no changes in product carbon. Consequently, in the discussion of the results, we simplify the discussion and generally refer only to additional sequestration of carbon.

Planted spruce seedlings
Photo by Ked Coffin, J.D. Irving, Ltd.

under the BAU—clearcut area limited to approximately 8.2 percent of the study area and at least 18 percent of study-area acreage remaining in unharvested areas for regulatory and conservation purposes.[24] While the primary impact on carbon results from increases in uneven-aged management, this scenario also reflects the effects of expanded planting in areas that are clearcut.[25]

- **Scenario 2—Expanding Plantations and Unharvested Areas:** This scenario is designed to show the impact on carbon sequestration of increasing acreage devoted to plantation silviculture and to unharvested areas. It illustrates the impact on carbon sequestration, above and beyond Scenario 1, of allowing a doubling of the levels of clearcutting and a further expansion of plantation forestry in these areas.[26] This is accompanied by an increase in unharvested areas beyond the 18 percent level in Scenario 1.

- **Scenario 3—Maximizing Total Sequestration and HWP Storage:** This scenario suggests an upper limit on the potential for silviculture to increase forest carbon. It maximizes sequestration over 60 years by removing all constraints on clearcut acreage while maintaining the Scenario 1 assumption that at least 18 percent of the study-area acreage is unharvested. Scenario 3, while generally agreed to yield socially undesirable outcomes due to impacts on ecosystem services, helps to illustrate important relationships between forest carbon maximization, silvicultural intensification in the form of plantations, and the corresponding carbon dynamics of unharvested areas.

For the BAU and the three alternative scenarios, we assume there is minimal future change in the forest products sector or opportunities with respect to carbon storage in wood products or wood waste materials. Real prices for biomass, pulp, and sawlogs are assumed to continue at recent levels, although we project a small annual decrease in costs faced by landowners on the assumption that some technological innovation occurs on the cost side. In these scenarios, technological innovation does not create

24 This minimum allocation to unharvested acreage is approximately equivalent to the percentage of the area currently covered by significant regulatory and conservation restrictions that affect harvests in northern Maine.

25 Planted acreage would double from around 5,000 acres per year to approximately 10,000 acres per year.

26 Planting in this scenario could potentially increase to 20,000 acres per year. While this represents a large increase from the current levels in Maine (about 5,000 acres per year), experience in New Brunswick suggests it is logistically feasible (personal communication with Greg Adams, FCCL Technical Team, November 10, 2022).

new opportunities for storing additional carbon in wood products.[27] A more detailed summary of the scenario assumptions is included in Table 2 below.

These three scenarios are not intended as policy recommendations. They are instead designed to serve as starting points for discussions of how carbon sequestration might be increased in northern Maine. We selected the scenarios to illustrate the predominant landscape-scale processes that result as different types of carbon-enhancing silvicultural treatments are implemented with the requirement that harvests be held constant over time. The FCCL modeling tools developed for this project will allow future researchers to test the ability of other combinations of silvicultural systems to enhance carbon sequestration and HWP storage and the additional costs of implementing these practices.

TABLE 02. Model Objectives, Constraints, and Forest Sector Assumptions for FCCL Scenarios

	SCENARIO			
	Business as Usual (BAU)	Expanding Uneven-Aged Silviculture (Scenario 1)	Expanding Plantations & Unharvested Areas (Scenario 2)	Maximizing Total Sequestration & HWP Storage (Scenario 3)
Objective	Max Net Revenues	Max C	Max C	Max C
Total Forest Area (ac)	7,583,441	7,583,441	7,583,441	7,583,441
Unharvested Area (ac)	1,390,296	1,390,296	>1,390,296	>1,390,296
Max Total Clearcut Area (ac)	973,392	619,314	1,238,629	7,583,441
Max Clearcut + Plant Area (ac)	247,030	619,314	1,238,629	7,583,441
Total Harvest (tCO2e/y)	7,340,000	7,340,000	7,340,000	7,340,000
Pulp + Biomass Harvest (tCO2e/y)	4,400,000	4,400,000	4,400,000	4,400,000
Saw Harvest (tCO2e/y)	2,940,000	2,940,000	2,940,000	2,940,000
Sawlog Prices ($/gt)	Historical Mean	Historical Mean	Historical Mean	Historical Mean
Pulp/Biomass Prices ($/gt)	Historical Mean	Historical Mean	Historical Mean	Historical Mean
Management Costs ($/ac)	Mean -0.25%/yr	Mean -0.25%/yr	Mean -0.25%/yr	Mean -0.25%/yr
HWP C Storage	Historical Mean	Historical Mean	Historical Mean	Historical Mean

27 Climate policy studies often consider a range of scenarios that reflect alternative futures. These allow researchers to explore how policies may perform given the significant uncertainties that exist about what the world will look like in coming decades and, more specifically, how it will respond to the challenges of climate change (Kriegler et al. 2014, O'Neill et al. 2020). Our analysis considered two alternative futures designed to show how deviations from current trends in the forest products sector (e.g., movements in the demand for wood products, changes in real price levels, technological innovation) would affect our estimates of carbon sequestration and the costs of incentivizing changes in silvicultural practices. The results of this work are presented only in Appendix C as they do not significantly alter the main conclusions of the report.

05

FCCL MODELING RESULTS

Photo by Lauren Owens Lambert

The FCCL analysis estimates the potential for shifts in silvicultural practices, applied across northern Maine's commercial timberlands, to increase carbon. The sections below describe the carbon results assuming continuation of current trends in the forest products sector. The analysis addresses leakage, cost-effectiveness, and other non-carbon benefits and costs of increasing the area devoted to carbon-enhancing silviculture in northern Maine while maintaining harvest rates to support Maine's forest products economy and rural communities.

CARBON SEQUESTRATION IMPACTS

Business as Usual

The BAU scenario, described in detail in Table 2, has the goal of projecting a future based on continuation of recent silvicultural practices in northern Maine that maintains historic harvests of approximately 7 million green tons (7.3 MtCO2e/y) of timber per year. The analysis estimates that about 6.2 million acres of the study area (82 percent)—roughly 140,000 acres per year—would need to be harvested over the model's 60-year timeframe to meet the 7.3 MtCO2e/y harvest objective. The remaining 1.4 million acres (18 percent) would remain in unharvested areas (Figure 4a) in the BAU. These acreage estimates are consistent with historical trends for harvests and with existing acreages for conservation reserve and set-aside areas (including riparian buffers) in the region (Daigneault et al. 2021).

In the BAU scenario, using MIFSM to maximize annual net revenues for landowners, net forest sequestration is estimated to average 3.6 MtCO2e/y. This generates annual net revenues of $77.5 million per year from harvesting 7.3 $MtCO_2e$ of timber per annum (Table 3).[28] The timber and revenue estimates are roughly consistent with harvest levels and stumpage prices that landowners have reported receiving in recent years (Maine Forest Service, n.d.).

In the BAU, 99 percent of the carbon sequestration is generated from the partial harvest (62 percent) and unharvested (37 percent) areas (Figure 4b). Clearcuts with planting produce 1% of the total annual sequestration in the BAU, while the clearcut with natural regeneration and regular shelterwood treatments combine to emit about 0.37 $MtCO_2e/y$). Regular shelterwood (36 percent) and clearcuts (23 percent) combine to produce 59 percent of the harvested timber in the BAU, with partial harvesting making up the remaining 41 percent of the 7.3 $MtCO_2e/y$ (Figure 4c).

TABLE 03. FCCL Scenario Results

Estimate	Business as Usual (BAU)	Expanding Uneven-Aged Silviculture (Scenario 1)	Expanding Plantations & Unharvested Areas (Scenario 2)	Maximizing Sequestration & HWP Storage (Scenario 3)
C Sequestration (tCO2e/y)	3,613,497	4,350,475	4,555,255	5,110,665
Forest Area	7,583,441	7,583,441	7,583,441	7,583,441
Annual Net Revenue ($/y)	$77,466,139	$65,838,942	$67,851,458	$85,964,970
Annual Harvest (tCO2e/y)	7,340,000	7,340,000	7,340,000	7,340,000
CHANGE FROM BASE (BAU)				
C Sequestration (tCO2e/y)	-	736,978	911,480	1,466,890
Annual Harvest (tCO2e/y)	-	0	0	0
Annual Net Revenue ($/y)	-	$-11,627,197	-$9,614,681	$8,498,831
Break Even Carbon Price ($/tCO2e)	**-**	**$15.78**	**$10.21**	**-$5.68**
Break Even Implementation Cost ($/ac)	**-**	**$151.43**	**$108.58**	**-$85.79**
% Change Carbon Sequestration	**-**	**20.4%**	**26.1%**	**41.4%**

28 The net revenue is calculated using MIFSM's estimate of mean annual harvest revenue less management, harvest, and transport cost, based on average harvest levels for each of the 108 forest type combinations, measured over a 60-year period. For more information on the price and cost data underlying these estimates, see Appendix C.

FIGURES 04A–C. Forest Area, Carbon Sequestration, and Harvests by Treatment

Alternative Silviculture Scenarios

Overall, the FCCL modeling indicates that, compared to the BAU scenario, wider-scale implementation of carbon-enhancing, uneven-aged management systems across the landscape, coupled with greater planting of clearcuts, could provide meaningful increases in carbon sequestration (Table 3). Forest sequestration could be increased further by approaches that make additional land available for more plantation management silviculture, which also results in more land allocated to unharvested areas. The three scenarios discussed below illustrate the underlying silvicultural and landscape dynamics of these processes.

Photo by Twolined Studio

Scenario 1: Expanding Uneven-Aged Silviculture

Scenario 1 primarily illustrates the forest carbon potential of expanding the use of uneven-aged management, which in our silvicultural framework includes both the continuous cover and irregular gap systems. From a modeling perspective, in this scenario the primary change from the BAU is to maximize carbon sequestration instead of annualized net revenues. Clearcut acreage is reduced somewhat from BAU levels and at a minimum the model must maintain BAU allocations to unharvested areas.[29]

Under these constraints, the model identifies a portfolio of silvicultural practices (Figures 4a–c: Forest Area, Carbon Sequestration and Harvests by Treatment) that are projected to increase carbon sequestration while meeting the harvest target. The modeling suggests that implementation of these alternative practices would increase carbon sequestration by 20 percent. This results in an additional 737,000 tCO2e/y across the study area (Table 3).[30] This is due to transitioning over the 60-year time frame from a landscape that is managed in the BAU primarily by partial harvest and regular shelterwood to one where approximately 56 percent of the area is in continuous cover forestry, 12 percent is regular shelterwood, 8 percent is clearcut and plant, 6 percent continues to be managed by partial harvests, and 18 percent remains in unharvested areas.

In this scenario, over the 60-year time horizon, the sequestration is split about equally between lands managed

29 In the BAU, planting was restricted to approximately 5,000 acres—roughly 25 percent of the acreage available for clearcutting each year in our modeled BAU scenario. In Scenario 1, we make the assumption that the clearcut area is constrained to approximately two-thirds of the BAU level but all of it is available for planting. Of the 737,000 tCO2e sequestered in Scenario 1, approximately 100,000 tCO2e (about 14 percent) is attributable to the increased sequestration from unharvested areas created as a result of the increased planting of clearcut areas. Holding planting constant at BAU levels in Scenario 1, sequestration would have increased by 17.6 percent instead of 20.4 percent.

30 As a point of reference, Maine emits approximately 17 million tons of CO2e per year.

TABLE 04. Continuous Cover versus Irregular Gap Comparison

Estimate	Business as Usual (BAU)	Expanding Uneven-Aged Silviculture (Continuous Cover)	Expanding Uneven-Aged Silviculture (Irregular Gap)
C Sequestration (tCO2e/y)	3,613,497	4,350,475	4,147,584
Forest Area	7,583,441	7,583,441	7,583,441
Annual Net Revenue ($/y)	$77,466,139	$65,838,942	$69,518,868
Annual Harvest (tCO2e/y)	7,340,000	7,340,000	7,340,000
CHANGE FROM BASE (BAU)			
C Sequestration (tCO2e/y)	-	736,979	534,087
Annual Harvest (tCO2e/y)	-	0	0
Annual Net Revenue ($/y)	-	-$11,627,197	-$7,947,271
Break Even Carbon Price ($/tCO2e)	**-**	**$15.78**	**$14.88**
Break Even Implementation Cost ($/ac)	**-**	**$151.43**	**$107.40**
% Change Carbon Sequestration	**-**	**20.4%**	**14.8%**

by continuous cover and areas left unharvested. Harvests (Figure 4c) come primarily from lands managed by continuous cover (64 percent).

Additional modeling and sensitivity analysis suggests the benefits of expanding uneven-aged management are not limited to continuous cover forestry (Table 4). Expanding the use of irregular gap silvicultural systems appears to offer roughly comparable opportunities for increasing carbon as continuous cover forestry. Under an alternative optimization analysis where continuous cover is assumed to be unavailable, MIFSM's optimal carbon maximization result identified 4,067,681 acres for treatment with irregular gap, as compared with 4,234,784 when continuous cover is available as a treatment (Figure 5a–c). This represents a sequestration increase relative to BAU of 15 percent under irregular gap compared to 20 percent in the continuous cover alternative. Thus, while continuous cover is estimated to provide greater climate benefits (i.e., a more optimal solution), irregular gap still provides meaningful increases in carbon sequestration and provides habitats for a broader array of wildlife species. Given the challenges implementing uneven-aged management treatments in LANDIS-II (see Section 3.1.2), in our view, the carbon sequestration difference between irregular gap and continuous cover is probably within the uncertainty range of our modeling for these two scenarios.

FIGURES 05A–C. Expanding Uneven-Aged Silviculture Scenarios: Forest Area, Carbon Sequestration, and Harvest by Treatment

Scenario 2: Expanding Plantations and Unharvested Areas

Scenario 2 considers the impact on carbon sequestration of allowing an expansion of plantation silviculture. This is modeled by relaxing the Scenario 1 constraint on the fraction of the study area available for implementing clearcut systems (both naturally regenerated and planted). In this scenario, the acreage potentially available for clearcutting in the study area—8 percent in Scenario 1—is assumed to double to 16 percent. We assume this entire area is available for plantations.

Young spruce plantation
Photo by Ked Coffin, J.D. Irving, Ltd.

The results of Scenario 2 suggest that adding to the acreage available for intensive, plantation-style management has the potential to further increase carbon sequestration. In this scenario, creating opportunities for an additional 10,320 acres of plantation each year allows an increase in carbon sequestration relative to the BAU from 20 percent in Scenario 1 to 26 percent in Scenario 2. This represents an additional 174,502 tCO2e/y each year, bringing the total sequestration increase to 911,480 tCO2e/y (Table 3).

The result comes from taking full advantage of the opportunity to implement clearcut and plant systems on all the available 16.4 percent of the study-area landscape, coupled with an increase from 18 to 21 percent in the unharvested areas and related reductions in regular shelterwood, partial harvest, and continuous cover forestry.

More detailed examination of Figures 4a–c: Forest Area, Carbon Sequestration, and Harvests by Treatment suggests that as more area is devoted to plantations, the required harvests come from a smaller portion of the land base. This allows a greater portion of the remaining acreage to remain in unharvested areas that efficiently sequester carbon. Harvests goals are met while net sequestration across the landscape is increased.

Although Scenario 2 illustrates the impacts of increasing use of plantation silviculture as an add-on to increased use of uneven-aged management, plantation silviculture could be implemented independently to increase forest carbon. This is an area for future research using the MIFSM model if such an approach appears feasible and socially acceptable.

Scenario 3: Maximizing Total Sequestration

Removing all constraints on the area devoted to intensive, plantation-style management has much more dramatic effect on carbon, increasing total sequestration to more than 41 percent above BAU levels (Table 3). As shown in Figure 4a, this focus on maximizing carbon is accomplished by the model choosing to increase the area devoted to clearcuts to 55 percent of the modeled landscape

(4.2 million acres) in tandem with boosting unharvested areas to 43 percent of the study area (3.3 million acres). It is the high growth rates of the plantations coupled with their ability to supply all the harvest needs in combination with efficient sequestration in the unharvested areas that combines to maximize carbon gains. In total, the unharvested areas account for over 80 percent of the carbon sequestration, with the clearcut lands accounting for almost all the remaining sequestered carbon (Figure 4b).

Scenario 3 is clearly an extreme case and does not itself provide a realistic option for carbon and silviculture policy. We view allocating 55 percent of the study-area landscape to clearcut-and-plant silviculture as a nonstarter from an ecosystem services perspective. But we include the scenario because it suggests several important insights that can shape how forest carbon policies are discussed and developed. First, any single-minded focus on maximizing forest carbon is not a realistic strategy; it needs to be informed by other ecosystem service and economic considerations. Second, the degree of silvicultural intensification is an important determinant of the overall potential for increasing forest carbon in northern Maine. The modeling suggests that going beyond the forest carbon increases that can be achieved with greater use of uneven-aged management would require increased use of plantation-style silviculture. Third, if there is some public appetite to incentivize more forest carbon sequestration by allowing additions to timberland acreage under plantation management, the analysis found there is no particular natural stopping point short of the 55 percent maximum. Increases in acres devoted to clearcut-and-plant silviculture steadily improve carbon sequestration by continuing to free up more sequestration capacity in unharvested areas until a rough equilibrium between the two is reached. Finally, this suggests that if increasing plantation silviculture is determined to be a policy worth pursuing, there would need to be an explicit public discussion of the trade-offs—more plantations and simultaneously more unharvested acres—of allowing more land to be devoted to these practices.

Clearcut with regenerating sugar maple, spruce, and fir
Photo by Ked Coffin, J.D. Irving, Ltd.

Additionality and Leakage

The FCCL modeling suggests a positive answer to the original question of whether silviculture can increase carbon while holding harvests constant (e.g., without resulting in leakage). The results presented in Table 3 show that carbon sequestration could be increased meaningfully—by at least 20 percent—while holding average harvests constant at approximately 7.3 $MtCO_2e/y$ over the 60-year modeling horizon, assuming that efficient policy instruments could be developed to induce landowners to participate in such a program.

This conclusion is important from both the research and practical perspectives. It demonstrates that a carefully designed carbon program implemented across northern Maine's commercial timberlands has the potential to provide real, additional, non-leaking climate benefits while still supporting Maine's forest products economy and rural communities. Existing forest carbon offset programs have been criticized both for using methods that do not ensure additionality and that employ insufficient adjustments for leakage (Haya 2019). By ensuring harvests continue at BAU levels and that carbon sequestration is additional to the baseline, we have demonstrated the potential for real climate benefits without leakage. A forest carbon approach that can demonstrate true additionality coupled with minimal to no leakage avoids the uncertainties associated with accurately projecting leakage in existing and efficient forest products markets. In theory, these types of carbon credits would be worth more to buyers than credits less likely to benefit the environment.

But the leakage conclusion is subject to an important caveat that stems from our modeling approach and assumptions. In our LANDIS-II modeling, while the 7.3 MtCO2e/y harvest target was met on average over the modeling period, we could not run enough iterations to fully calibrate LANDIS-II to ensure the harvest target was met every year (or at least every decade). Consequently, in parameterizing MIFSM, we chose to constrain the model using average harvest rates over the entire 60-year modeling horizon, rather than constraints ensuring that the harvest goal was achieved at shorter time intervals for each forest type. Therefore, while our results indicate that harvest targets can be met over the longer modeling horizon and that net leakage over the 60-year modeling horizon is zero, the analysis does not ensure that there will not be positive or negative leakage from year to year or decade to decade within our modeled time horizon.[31] From a landowner perspective, this has important implications for net revenues that warrant further exploration at finer temporal scales (e.g., maintaining harvest rates over five-year intervals).

Cost-Effectiveness

The FCCL modeling also addresses the costs of incentivizing carbon-enhancing silviculture. Commercial landowners currently do not widely employ certain types of silvicultural practices (e.g., continuous cover and irregular gap systems) selected for inclusion in our study because they are not always feasible or profitable for many or most types of stands or forest ownership types. Hurdles to adoption of these systems on a more widespread basis include limited demonstration areas, the expected expense (and attendant adverse effect on landowner net revenues), logging contractor systems optimized for production under more commonly used silvicultural systems, future uncertainty regarding prices and markets for products, and simple inertia.

When maximizing carbon, the FCCL model estimates how much it would cost the landowner to implement carbon-enhancing silvicultural approaches based on

31 For the harvest constraint modeling, we used decadal harvests that averaged 7.3 MtCO2e over our 60-year study horizon as the target. While there were some decadal fluctuations around this mean in our modeling, these were not dramatic and were more a function of how the LANDIS modeling was specified than what would happen in reality. It is our hypothesis that with more time and resources, we could have tweaked the decadal acreages harvested in LANDIS to meet the decadal 7.3 MtCO2e/y targets more consistently, without having much of an effect on the sequestration estimates. For more information on the LANDIS harvest estimates used in the model, see here.

Photo by Charlie Reinertsen

available information. Comparing scenarios, the difference in annual average net revenues between a scenario and the BAU provides an overall indicator of the opportunity costs landowners face in transitioning to alternative silvicultural practices. We can put these on a per-ton-of-CO2e basis by dividing the change in average annual net revenues by the average annual net change in sequestration to estimate what landowners would need to be paid on average per ton of additional CO2e to switch to carbon-enhancing silviculture. This measure reflects today's costs of implementing the silvicultural practices. This creates a metric commonly used for comparing approaches for mitigating carbon.

In the real world, the payment of incentives would be complicated by the actual timing of the transactions. For example, if a landowner were not compensated until there was a demonstrable increase in sequestration over the modeled base case, the seller would expect to be paid the cost of the practice, plus a risk-adjusted return on their invested capital for the time period between the silvicultural expense and the carbon payment. As this calculation lies beyond the capabilities of our model, we use the up-front incremental management cost per expected incremental ton of carbon sequestration as a metric. For the purpose of comparing our estimates with those in the literature, this provides a consistent and transparent approach.

Assuming continuation of current forest product sector trends, average cost-effectiveness is approximately $16/tCO2e in the scenario that illustrates expansion of uneven-aged management (Scenario 1). This falls to $10/tCO2e in Scenario 2 where we allow an expansion of plantation-style silviculture accompanied by an increase in unharvested areas (Table 3). From a carbon mitigation perspective, the available literature suggests that these changes to silvicultural practices will likely prove cost competitive over the long run. For comparison, Gillingham and Stock (2018) provide estimates of the costs of reducing CO_2 emissions. These range from about $20/tCO2e for onshore wind to over four times that much for generation technologies that incorporate carbon capture and storage. In addition to being cost competitive, carbon-enhancing silviculture also has side benefits to the state of Maine in supporting the forest products industry and forest-dependent communities in northern Maine.

We also translated these landowner opportunity costs into a mean cost per acre. This was done by dividing cumulative change in revenue over the entire study period by the number of acres that the model estimated would change practice from the BAU over that time. For example, Scenario 1 estimated that 4.6 million acres of partial harvest, regular shelterwood, and clearcut with natural regeneration would be converted to continuous cover and clearcut and plant at a cumulative cost of $696.6 million over the 60-year period. This equates to an average cost of $151/acre.

It is also instructive to consider the social cost of carbon (SCC). The SCC is a measure of damage created by emitting one additional ton of carbon dioxide to the atmosphere. The SCC includes property damages due to sea level rise, injuries to agricultural crops, the value of adverse impacts to human health, etc. (Rennert and Kingdon 2019). Currently, the U.S. government uses an estimate of \$51/tCO_2e for the SCC (Interagency Working Group on Social Cost of Greenhouse Gases 2021). Again, from this perspective, paying landowners \$16/tCO_2e to avoid \$51 in climate damages would be a relative bargain.

Despite their apparent cost-effectiveness, translating the opportunity costs of alternative silvicultural systems into dollar-per-acre values makes clear that these are not trivial for landowners. In the case of approaches that rely primarily on a major expansion in uneven-aged management, a landowner committing to change practices in the near term would require payments of somewhere in the range of \$100–\$150 per acre (Tables 3 and 4). Allowing a further expansion of more intensive silviculture as illustrated in Scenario 2 reduces the opportunity costs, but our modeling suggests it would still require a payment of slightly over \$100 per acre to compensate landowners for their additional costs. These per-acre estimates reinforce why incentives are needed to convince landowners to adopt silviculture that enhances carbon sequestration.

American marten is one wildlife species that requires large blocks of closed canopy forest

Non-Carbon Benefits and Costs

In addition to storing more carbon, implementation of carbon-enhancing silvicultural strategies has the potential to generate an array of other non-carbon benefits and costs. As our modeling work makes clear, some of these carbon-enhancing silvicultural practices simultaneously create benefits and costs that require policy makers and the public to weigh carbon and non-carbon trade-offs explicitly. A good example is the case where opening additional land to plantation silviculture results in more carbon sequestration, may have negative biodiversity impacts on the more intensively managed acres, but potentially creates biodiversity benefits on the areas that are added to unharvested acreage. In this regard, the types of habitats that result from different forms of silviculture are known to be predictable. Further, based on work by Simons and Harrison (Simons et al. 2010) and DeGraaf et al. (2005), the habitat needs of the wildlife of the forests of northern Maine are also known. Managing at least approximately one-quarter of the forested landscape with patch cuts that create early successional habitat and at least one-sixth of the landscape in large (around one square mile) blocks of closed canopy forest will serve the habitat needs of the great majority of current wildlife.

Similarly, the adoption of carbon-enhancing silviculture can generate important economic impacts. Silviculture that reduces rotation ages and shifts harvests toward wood products that store carbon over longer time frames—which are possible but which we have not explicitly analyzed in Scenarios 1 through 3—could create new industries, generating economic growth for Maine's forest products sector and rural communities. But incentives that promote shifts toward these types of silvicultural practices also can create financial risks for landowners. While these might be minimized through incentive instrument design, any residual risks would need to be weighed against the carbon benefits of any incentive program.

Overall, non-carbon benefits and costs are beyond the scope of this study. But they should be an important factor in any final assessment of appropriate strategies for incentivizing forest carbon silviculture. Clearly, our study shows that silvicultural interventions could lead to more sequestered carbon in northern Maine's forests and wood products. But these same interventions can have positive and negative impacts on forest ecosystem services, the forest products sector, and northern Maine's rural economy. This is an area that requires further analysis as part of future efforts to design and implement forest carbon incentives.

SUMMARY MODELING INSIGHTS AND CAVEATS

Overall, the FCCL modeling demonstrates that:

- Northern Maine's forests already sequester and store substantial amounts of carbon each year, both in growing forests and in HWPs. Under BAU, our modeling suggests that the forests in our 7.6-million-acre study area contribute 3.6 MtCO2e/y of net sequestration in live tree biomass and long-term storage in HWPs after adjustments for growth, decay, and harvests.

- Increasing the adoption and application of alternative silvicultural systems in northern Maine's commercial timberlands has the potential to further increase carbon sequestration beyond BAU levels, while maintaining timber harvest levels that will support the forest products economy and rural communities as well as maintaining wildlife habitat and biodiversity. Expansion of uneven-aged forestry, such as irregular gap and continuous cover systems, offers one avenue for increased carbon sequestration; plantation silviculture coupled with increases in unharvested areas offers another. Modeling suggests that increases in sequestration of 20 percent are possible with expansion of uneven-aged silviculture, and this could be increased further if greater use of plantation silviculture, coupled with allocation of more land to unharvested areas during our 60-year modeling period, is deemed a reasonable public policy trade-off.

- Our modeling indicates that the projected costs of compensating landowners for shifting to silvicultural systems that sequester more carbon are likely to prove competitive when compared with other technologies and approaches for reducing the impacts of climate change.

- If policies can be put in place that incentivize adoption of these silviculture systems, while holding harvests at BAU levels in the future, the newly sequestered and stored carbon would be truly additional and not subject to leakage over the long term—features that are not assured under the rules of many existing carbon offset programs. Even were leakage not an issue, it is important to recognize that enhancing carbon storage is consistent with maintaining a robust forest economy in Maine.

Photo by Twolined Studio

Nonetheless, it is also important to recognize the many questions that our modeling has not answered and that would need to be addressed to support the development of an implementable incentive program that would make the carbon results of our work a practical reality.

One question relates to how public policy makers resolve trade-offs between silvicultural incentive approaches that have acceptable average costs, generate different levels of net climate benefits, but potentially create differing impacts to other resource values, for example negative impacts to biodiversity. As our analysis makes clear, this would likely be the case if a greater area of northern Maine's forested landscape were to be devoted to clearcut-and-plant silviculture. As more area is put into plantations, the required harvests can come from a smaller portion of the land base. This allows a greater portion of the remaining acreage to be unharvested (or potentially managed with alternative silvicultural systems, including uneven-aged options such as irregular gap and continuous cover systems). This finding harkens back to the triad approach introduced by Seymour and Hunter (1992), who suggested allocating specific areas into intensively managed, extensively managed, and reserve zones to achieve multiple objectives. Determining the "right" percentage of acreage to put into more intensive management is a question our modeling can inform but not answer.

There are also technical questions and issues that this study has highlighted but been unable to address. While the modeling suggests that carbon can be increased while holding harvests constant when averaged over the study's 60-year time horizon, the modeling has not been able to answer the question of how much carbon would be increased if *annual* (or decadal) harvests were held constant rather than harvests averaged over 60 years. This would be a critical practical detail to resolve when designing a program to implement an incentive system.

It is also worth noting that the model's ability to differentiate product output (quantity and quality) could be improved. Our version of LANDIS did distinguish between old/young wood (+/- 40 years), which we used as a proxy for pulp/sawtimber. Thus, the less intensive practices like continuous cover and irregular gap did produce LANDIS results with a higher proportion of the harvest contributing to sawtimber. (See

Appendix C, Table 6). But the decision to hold both total harvests constant and the ratio of pulp to sawlogs prevented shifts toward greater carbon in HWPs. For these reasons, the modeling of practices like continuous cover and irregular gap, as well as clearcut and plant, would understate the carbon benefits from silviculture that promotes more sawtimber if there is market demand for these long-lived, durable wood products. The LANDIS/MIFSM approach used for this study could certainly benefit from further refinement in this area, which we expect would further increase carbon stored in HWPs.

In addition, our study results would benefit from further benchmarking and calibration. The LANDIS-II modeling has not been rigorously benchmarked for all our silvicultural systems, particularly the more complex irregular gap and continuous cover systems for which LANDIS algorithms were developed specifically for this project. While the behavior of these systems in LANDIS-II appears broadly consistent with the expectations of our silvicultural experts, further testing and calibration is needed. As noted previously, silvicultural prescriptions that rely on thinning to improve stand quality were challenging to implement in LANDIS. Comparisons with other forest growth and yield models, for example FVS, may prove useful. Until that time, the results for continuous cover and irregular gap should probably be viewed as roughly equivalent and fine distinctions between these systems should not be made.

More generally, the LANDIS-derived estimates of carbon sequestration in the FCCL study for uneven-aged management systems appear to be lower than those from other recent studies when normalized for harvest rates (Pounch and Giffen 2021, Meyer et al. 2022, Puhlick et al. 2020). The specific reasons for this are unclear but could be related to differences in forest types and productivity, changes in harvest levels across practices and/or scenarios, the model accuracy and approach (where relevant), differences in BAU assumptions, forest manager expertise (if derived from an empirical study), or some other unidentified factor. Nonetheless, the direction and magnitude of the changes in forest carbon sequestration is similar across all these studies.

Notwithstanding these caveats, the results presented here provide strong theoretical support for encouraging the adoption of alternative silvicultural systems in Maine, including both intensively managed plantations and lighter-touch uneven-aged forestry systems such as irregular gap and continuous cover. Ultimately it is likely the case that northern Maine's commercial forest landowners will need flexibility to employ diverse forest management practices. In that context, one means of encouraging greater use of the alternative systems would be the development of incentive systems that encourage landowners to voluntarily adopt these practices where they make economic and financial sense for an individual owner and their particular land base. How such an approach might be implemented is the subject of the final section of this report.

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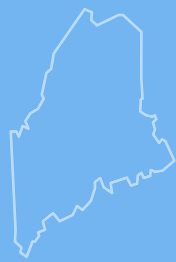

FOREST CARBON INCENTIVES: POLICY OPTIONS

INTRODUCTION

As noted above, applying a portfolio of silvicultural systems across northern Maine's forested commercial timberland shows potential for sequestering and storing more carbon while maintaining prevailing timber harvest levels, thereby realizing climate benefits while supporting Maine's important forest products industry and rural communities. The key policy challenge for implementing a forest carbon program that is truly additional and not subject to leakage is ensuring that harvests continue at BAU levels as new silvicultural systems are incentivized. One possible avenue is reform of existing carbon offset markets to ensure that additionality and non-leakage requirements are met. Such reforms are an ongoing topic of discussion in the carbon offset world and are beyond the scope of this report.

We note, however, that such reforms could make it more difficult for landowners to participate in carbon markets, and even before reforms, participation in offset programs had been slow to catch on in Maine due to a host of real-world impediments. These stem from high transaction costs, including lack of upfront cash for investment in silviculture, extensive monitoring and verification requirements, and uncertainty about the future. Whether ongoing reforms in offset markets will adequately address these issues is an open question.

Consequently, going forward the FCCL team suggests looking beyond policy tools focused only on carbon offsets and instead to practice-based silvicultural incentives. Under practice-based incentives, payment is made for implementation of a specific silvicultural treatment that is expected to lead to increases in forest or product carbon, based on the best science available. For example, regulations and best management practices (BMPs) establish core expectations for timber management along watercourses because the science is well-established that riparian buffers keep the water clean. These buffers have been shown to be effective, and there is no need to measure water quality on every stream. In the same way, research tells us that certain silvicultural practices should result in more carbon storage. In theory, either private parties or governments could use pay-for-practice approaches to incentivize these types of silvicultural approaches, while


Photo by Lauren Owens Lambert

instituting less complex verification and monitoring regimes that need not be a burden to the landowner. Similarly, outside parties could pay landowners to maintain buffers wider than regulations and BMPs suggest, if they believed this to be a good value proposition.

Incentivizing practices instead of paying directly for carbon could have advantages in terms of reduced transaction costs, although this strategy poses potential trade-offs in the form of reduced certainty that the carbon benefits will be realized. Practiced-based incentives would also address the mismatch in timing between the cost incurred by a landowner and the carbon benefit produced later on. With an upfront payment, the landowner would not have to be compensated for assuming performance or pricing risk over time. A premise of this report is that these trade-offs merit further public discussion and debate, especially if there is potentially significant public benefit to a meaningful increase in forest carbon sequestration on large commercial forest lands.

The remainder of the discussion in this section describes some examples of practice-based instruments that might be used to implement forest carbon incentives in Maine. The focus is primarily on incentives with the potential to achieve the kinds of results presented in the modeling analyses described in this report. These policy options focus on incentive tools that ensure non-declining future harvests, which maintain economic activity and minimize the potential for leakage.

These incentive approaches are discussed at a conceptual level and would require more detailed analysis and development before actual implementation. The goal here is to outline schematically, for purposes of prompting further discussion in both the public and private sectors, incentive tools that might be useful in expanding the role of Maine's commercial timberlands in sequestering and storing carbon in coming decades. Many details would still need to be worked out, and some approaches might ultimately prove impractical. But the goal is to generate discussion around alternatives to conventional forest offsets.

PRACTICE-BASED INCENTIVE SYSTEMS

Our analyses indicate potential roles for the expanded adoption of plantation silviculture and uneven-aged forestry in a portfolio of systems designed to sequester more carbon across Maine's commercial forest landscape. But since these practices are not currently economic to implement for most stands and/or for most landowner circumstances, payments could be made to landowners on a per-acre basis to subsidize their adoption.

Programs to subsidize forestry practices are quite common, although historically they have generally been available only to small landowners. Examples include the USDA's Natural Resources Conservation Service (NRCS) programs that pay small private landowners to undertake forest improvement practices like thinning in overstocked stands (Natural Resources Conservation Service, n.d.). In New Brunswick, the provincial government has supported similar programs that pay landowners for pre-commercial thinning and various other forms of site preparation, planting, and management planning (SENB Wood Marketing Board, n.d.). Nova Scotia also had an extensive program paying landowners to implement forest management practices from the 1980s to 1995 (Appendix D). Programs like these could be adapted to promote the implementation of silviculture that would enhance carbon storage in northern Maine.

Our analyses, however, indicate that the opportunity cost for landowners of implementing silvicultural shifts that enhance carbon could be substantial, both on a per-acre basis and in aggregate if large quantities of carbon are to be sequestered—the average costs are between roughly $151 per acre assuming a large expansion of uneven-aged management and $109 per acre if the expansion of uneven-aged management is augmented by a doubling of the area currently managed for plantation silviculture. In northern Maine these practice changes might be desirable over millions of acres in coming decades.[32] This indicates a sizable required investment cost but one not inconsistent with the carbon benefits demonstrated by our analysis.

The program concepts outlined below generally assume—because of the scale of the efforts and the complementary benefits to Maine's economy, communities, and natural resources as well as to global GHG mitigation efforts—that government provides the subsidies for practice-based incentives. This is not to say, however, that other entities (e.g., NGOs, private corporations) might not also play a role in the development of practice-based incentive programs. The Family Forest Carbon Program is an example of an existing initiative to pay landowners for carbon-enhancing changes to their forest management practices.[33]

Potential sources of funding for government-sponsored practice-based incentives encompass the full range of options for funding climate policies, and detailed analysis of these is largely beyond the scope of this report. But in general, sources could include federal and state taxes as well as more targeted revenue sources such as receipts from government permitting programs, user fees, bonding efforts, etc. To the extent state government became the owner of additional carbon through its funding of practice-based incentives and could demonstrate broad increases in carbon stemming from its investments in silviculture—for example through regular remote sensing efforts—the state might follow up on the report of

32 Note this is less than the EQIP payments to small landowners for many practices, but EQIP has never been implemented at the scale needed to make an impact for climate.

33 The American Forest Foundation and the Nature Conservancy developed the Family Forest Carbon Program (https://www.forestfoundation.org/what-we-do/increase-carbon-storage/family-forest-carbon-program/), which currently is open to family forest landowners in several eastern U.S. states.

the Governor's Forest Carbon Task Force and consider developing, in conjunction with other programs, a Maine-specific program to sell carbon offsets and use the proceeds to pay the costs of practice-based forest carbon incentive programs. State involvement could boost confidence and hence sales, increase landowner participation and increase the value per ton of carbon

Photo by Twolined Studio

Fixed Price and Reverse-Auction Systems

Practice-based forest carbon incentives designed to implement the portfolio approach suggested by our modeling could take several forms. A fixed-price incentive would simply set a price and quantity objective for each practice over some specified time frame for a specified number of acres (repeated every five years, for example) and offer landowners that fixed amount for agreeing to a management plan implementing the practice over an agreed-upon time period. This is effectively the system that NRCS uses to promote changes in small landowner behavior that yield a public benefit. Nearly all commercial forest landowners already keep track of all acres harvested or treated each year, often via a spatially explicit GIS system, so monitoring and reporting of the implementation of various carbon-enhancing silvicultural systems would not incur new monitoring cost.

Alternatively, instead of specifying a fixed payment for adopting the practice, an agency or other organization could use a reverse auction to allocate incentives to landowners willing to switch to specified carbon-enhancing silvicultural practices. Under this approach, landowners would place bids with the auctioneer reflecting the price they would be willing to accept per acre to manage their lands using the requested silvicultural approach and the number of acres they are offering to manage at that price. The auctioneer could then accept the bids, starting with the least expensive, up to the bid where it reaches the number of acres determined to be the optimal total amount to place under management by that silvicultural system from a carbon perspective during that time frame.[34]

Reverse auctions have been used by a wide array of public and private entities in recent decades for the acquisition of goods and services (Phillips 2010). There are also recent precedents for using them to promote carbon storage in forests. NCX, a provider of forest carbon offsets, has used reverse auctions to solicit bids from landowners wishing to participate in markets for the sale of single-year deferrals of forest harvests.

Both the fixed-price and reverse-auction approaches would have potential advantages and disadvantages as a basis for incentivizing forest carbon.

34 The cutoff for accepting bids might be where the agency meets its budget constraint rather than the desired acreage, which might lead to a suboptimal result.

The main advantage of the fixed-price approach is its simplicity. If the agency wants to ensure that roughly 50 percent of the landowners find the program attractive, it will determine the incentive level at which half the landowners benefit economically by participating. Every participant would be compensated with the same incentive payment. In concept, the program could limit funding to a certain number of acres, thereby giving the agency some control over the scale of implementation. To implement the portfolio of silvicultural systems across the landscape, 10-year targets could be established for each silvicultural system, proportional to the decadal targets established by modeling of the type conducted for this study. Over time, this would lead to a landscape approximating the distribution of practices found optimal for carbon in our modeling exercises.

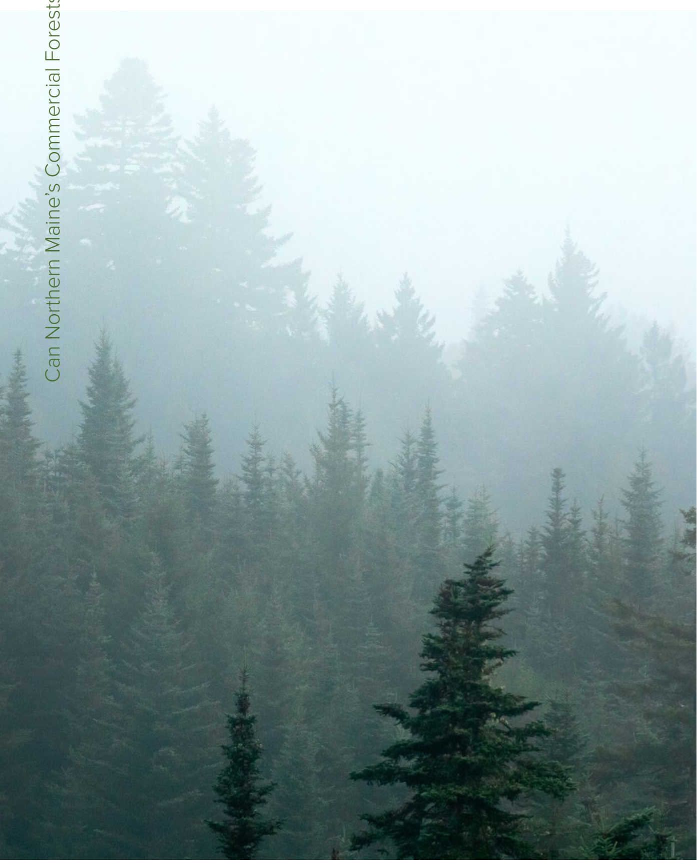

Photo by Lauren Owens Lambert

The primary disadvantage of the fixed incentive is its economic inefficiency. Not every landowner faces the same costs of switching to the alternative silvicultural practices. Their timberlands may differ in terms of species, stand conditions, site attributes, access to markets and logging contractors, management costs, and a host of other factors that could affect the opportunity costs of alternative silvicultural systems. Under a fixed-incentive system, in order to attract those landowners with higher switching costs, the incentive will be higher than it needs to be for many landowners with lower switching costs. This makes the program less efficient than it would be if each landowner were paid only what is needed to offset the additional costs of the alternative silvicultural system.

The advantage of the reverse-auction approach is that it would pay each landowner what they say they need to make the change. While more complex administratively, this method for subsidizing carbon-enhancing silviculture is potentially much more efficient than the fixed subsidy approach. Consequently, the average payout cost per ton of carbon sequestered can be expected to be significantly lower, thereby providing greater climate mitigation benefits for any given total amount of available incentive funding.

A major challenge in organizing successful reverse auctions is ensuring adequate competition. In Maine's commercial timberland sector, this will require careful evaluation, given the relatively small number of firms holding a large percentage of the timberland. But if it can be determined that there will be enough bidders with enough acreage to support a competitive reverse auction—and this may well be possible if the auction is organized on a stand instead of a landowner basis—the benefits with respect to lowering the overall cost per ton of carbon sequestered may be substantial.[35]

35 Such an approach raises other challenges, however, in the form of potential leakage within an ownership.

Government Risk Sharing in Forest Carbon Projects

Governments also have the ability to incentivize carbon sequestration and storage through more novel approaches, for example sharing the risk associated with transitioning the landscape to carbon-enhancing silvicultural systems. New remote sensing technologies for tracking changes in carbon create opportunities that did not exist in the past for managing risk while reducing transaction costs.

As an example, consider a program where the government implements a reverse-auction system for moving the landscape toward a new mix of silvicultural systems over the next 60 years, holding auctions each decade that specify the acreage desired for transition to each silvicultural system. Under this system, agreements would require landowners to implement a land management plan demonstrating their continued compliance in carrying out the specified silvicultural treatments required under the proposed system. The agency would take ownership of any additional carbon beyond BAU quantities.[36] But here, no monitoring or measurement of carbon outcomes would be required of the landowner, although harvests would be capped at some agreed-upon level, estimated to be consistent with increasing carbon sequestration and storage.

The government agency running the program would employ remote sensing technology to track carbon gains across the large areas over which it has contracted the carbon rights. Using a technology such as that currently employed by NCX, (NCX, n.d.), transaction costs could be expected to be reduced substantially relative to on-the-ground carbon monitoring and verification protocols.

Essentially, under this approach, the public, through the implementing government agency, would assume the risk that the transition to the alternative silviculture does not increase carbon as much as the incentives assumed based on the best science available at the time.[37] Landowners would not be penalized for not realizing estimated carbon gains on their lands. At the same time, the public would be protected by the harvest caps that would keep landowners from economically benefiting from overharvesting and reducing carbon on their lands to below BAU levels.

Acquiring carbon rights from landowners also has the advantage of creating a program that ultimately could be self-financing. As it verifies the sequestration of additional carbon through its remote sensing and ground-truthing activities, a government agency could market the carbon to businesses in need of real, verifiable non-leaking offsets, reimbursing itself at least in part for the original payments to landowners. But it would be critical for the program to carefully monitor the carbon gains from those lands on which it has paid for practice shifts and

36 The AFF/TNC Family Forest Carbon Program (https://www.forestfoundation.org/what-we-do/increase-carbon-storage/family-forest-carbon-program/) is a practice-based incentive program that is similar to what is proposed here. The major difference in the proposal here is that it includes a reverse auction component and overall targets for percentages of the landscape in each practice in order to maintain harvest levels.

37 In concept, an NGO or private corporation running a similar practice-based program could also assume the risk that the carbon goals are not met by paying for the practice change in advance and not requiring repayment by the landowner if the carbon targets are not met.

therefore acquired the carbon rights. Otherwise, it would be unable to fully validate the carbon attributable to its practice-based incentives.

Again, such a novel system would need considerable development of the mechanisms for purchasing carbon from landowners, approaches that would allow land transfers to continue unimpeded, and potentially the creation of mechanisms allowing landowners to withdraw from the program while compensating the government for any carbon losses. In addition, further development would be needed to support robust remote sensing approaches for monitoring and verifying the sequestration across large areas of commercial timberland in Maine. But the advantages of such a program, in terms of reducing transaction costs and shifting of risks in ways that reduce impediments to landowner participation, in our view, make further exploration of such a program needed.

Why silviculture matters: these two stands are the same age, but the the top one was thinned, while the one on the bottom was left alone. At age 40, the thinned stand has large, well-spaced trees that will produce sawtimber in 10 years. Thinning is one practice that could be incentivized through a carbon-smart forestry program.
Photo by R. Alec Giffen

Loan Programs for Climate-Smart Silviculture

Interest-free or low-interest loan programs for landowners have the potential to stimulate additional investments in climate-smart silviculture. While perhaps not providing enough incentive to tip the balance for high-opportunity-cost silvicultural approaches, low- or no-interest loans could make a difference for certain practices in certain stands.

For example, in situations where planting, competition control, pre-commercial thinning or early commercial thinning have been demonstrated as practices likely to sequester more carbon than baseline practices (this study has only addressed the incremental carbon sequestration expected from planting after clearcutting), low- or no-interest loans could make capital available to landowners to implement these practices. Loans might also be made available to cover the up-front costs of planning and the subsequent monitoring and verification needed to track carbon sequestration. Loans could be paid off when landowners receive payment for additional sequestered carbon or harvest the timber from the stands improved with the silvicultural interventions.

An example of a similar type of program was an innovative agricultural loan initiative launched by the Farmers' Business Network that quantified the financial benefits of conservation practices and provided lower-interest loans to farmers implementing these practices (Environmental Defense Fund 2022).

07

CONCLUSIONS AND NEXT STEPS

FCCL STUDY GOAL

The FCCL project was designed to evaluate whether commercial forest landowners in Maine could increase carbon sequestration in the forest and in harvested wood products (HWPs) by employing various silvicultural practices that would cost-effectively mitigate greenhouse gas emissions while not reducing harvests over time.

LANDSCAPE-SCALE NORTHERN MAINE STUDY AREA

Our study considered 7.6 million acres of predominantly privately owned commercial forest lands in northern Maine. Under current management practices these lands are expected to provide net carbon sequestration estimated at 3.6 million tons of CO_2 equivalent (MtCO2e) per year over a 60-year time horizon while providing timber harvests of approximately 7 million green tons per year—equal to 7.3 MtCO2e—that support the northern Maine forest products sector and rural communities.

INCREASED FOREST CARBON SEQUESTRATION AND STORAGE

The FCCL work suggests that landscape-scale adoption of less widely used silvicultural systems has the potential to increase carbon sequestration and storage in HWPs without reducing harvests. Silviculture with the potential to increase carbon sequestration and storage includes a variety of systems that rely on thinning to improve quality and growth rates and approaches that use clearcutting and planting combined with leaving other areas unharvested. Under assumptions that current trends continue in the forest products sector, we project that transitioning a greater share of northern Maine's commercial timberlands to these carbon-enhancing silvicultural systems over the coming decades has the potential to increase carbon sequestration in the forest and in HWPs by upwards of 20 percent compared with current management practices. This equates to an estimated 737,000 tons or more of additional CO2e per year across the 7.6-million-acre study area over the 60-year study horizon. This estimate understates sequestration for the alternative silvicultural practices that raise the proportion of sawlogs harvested. This was not modeled in our study.

Photo by Charlie Reinertsen

COST-EFFECTIVE CLIMATE MITIGATION

As a basis for determining the cost-effectiveness of forest management as a carbon mitigation strategy in northern Maine, the study estimated the additional costs to landowners of implementing silviculture that sequesters more carbon. These costs appear competitive with other approaches for reducing carbon in the atmosphere. At the high end, landowners on average would need to be paid approximately \$16/tCO2e to make it profitable for them to adopt alternative silvicultural systems that store more carbon. This equates to an average up-front payment of approximately \$151 per acre. On a \$/tCO2e basis, these costs are very competitive with other climate mitigation measures like solar and wind energy.

TRUE ADDITIONALITY/NO LEAKAGE

The transition to alternative silvicultural approaches can provide increased carbon that passes both the additionality and leakage tests. The additional carbon sequestration identified by our research would not have existed without active implementation by commercial landowners of the alternative silvicultural practices evaluated in this study. Adoption of these practices would provide meaningful climate benefits that are not vulnerable to the additionality critiques undermining some carbon offset projects—the claim that carbon would have been sequestered anyway even in the absence of an incentive payment, and that the offset therefore provides no real climate benefit. Furthermore, our projected carbon increases would be achieved by applying forest management approaches where average harvest levels could be maintained at current levels over the study's 60-year time horizon, thereby avoiding leakage, the problem where increased carbon sequestration in one region is negated by increased timber harvests and carbon emissions in another, again resulting in no net climate benefit.

NEW FOREST CARBON POLICY MODELING TOOL

The FCCL work has created a valuable tool for evaluating the opportunities and trade-offs involved in deploying silviculture at a large landscape scale to achieve carbon goals. A key insight of our work has been to demonstrate that there are multiple ways of combining silvicultural systems across the landscape to increase carbon sequestration while maintaining harvest levels. Different mixes of silvicultural systems can provide different levels of increased sequestration across the landscape and in HWP storage. The mix of systems has important implications for the provision of ecosystem services (e.g., wildlife/biodiversity) and economic benefits. Understanding these opportunities and trade-offs is a critical task moving forward, which the FCCL model can help inform.

NEW OPPORTUNITIES FOR PRACTICE-BASED INCENTIVES

Implementation of carbon-enhancing silviculture across northern Maine's landscape will require innovative policy thinking to ensure more carbon is sequestered without reducing harvests. The FCCL team suggests that, in addition to ongoing efforts to improve forest offset markets, efforts to develop incentives should focus on how expanded use of practice-based programs might be used to implement carbon-smart forestry that is truly additional and non-leaking.

NEXT STEPS

Overall, the FCCL study should be viewed as a promising proof of concept—that Maine's commercial timberland owners could be incentivized at competitive costs to sequester more carbon across the landscape and in HWPs. But the FCCL work, while integrating a wealth of detail about silvicultural systems and forest economics, still relies on numerous simplifying assumptions that result in important uncertainties needing further exploration as part of the policy development process. Because some of the alternative silvicultural systems proposed have not been widely implemented, practiced, and studied at scale and over time on lands managed with a history of more conventional silvicultural systems, one initial goal would be to broaden the establishment of demonstration and study areas under programs like the Cooperative Forest Research Unit's Maine Adaptive Silviculture Network. Additional work with landowners is also needed to validate the results of the FCCL modeling at finer scales. In particular, there is (1) a need to demonstrate that harvests and net revenues can be maintained over shorter time scales and (2) to refine the carbon and product modeling for uneven-aged and plantation silvicultural systems through scenarios that include increased production of and demand for durable wood products. At the same time, stakeholder coalitions could be assembled to begin more detailed discussion about incentive design and implementation. For example, under the $30 million USDA Climate Smart Commodities grant recently awarded to the New England Forestry Foundation, pilot projects could test the effectiveness of incentive-based programs for promoting carbon-smart silvicultural practices. The FCCL study identifies important considerations, asks key questions, and lays initial groundwork for embarking on these processes. Support for these activities from the State of Maine could be instrumental in making carbon-smart forestry a reality.

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APPENDICES

The report's complete appendices are available at newenglandforestry.org/connect/publications/fccl.