FOREST CARBON

FOR COMMERCIAL LANDOWNERS APPENDICES

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

REPORT PREPARED FOR
the Forest Carbon for Commercial Landowners Initiative

LED BY RESEARCHERS FROM
University of Maine, New England Forestry Foundation and USDA Forest Service

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March 2023

Appendix A: Literature Review

Click here to access the literature review on Google Docs.

Appendix B: Impacts of PCT and ECT

Prepared by Dr. Aaron Weiskittel

Pre-commercial thinning (PCT) and early commercial thinning (ECT) have been shown to be effective management strategies in Maine's forests (Weiskittel et al. 2011; Benjamin et al. 2013; Bataineh et al. 2013). PCT has been shown to be an effective means of improving species composition to more desirable commercial species (Weiskittel et al. 2011), accelerating the growth of residual trees (Weiskittel et al. 2009), and increasing the sawlog proportion for a given tree size (Duchesne, Pitt, and Tanguay 2013). Over a rotation, PCT has been shown to increase the maximum net present value (NPV), while also decreasing the time it takes to achieve peak NPV (Hiesl et al. 2017). PCT can also be combined with commercial thinning methods to both accelerate growth and generate mid-rotation revenue (Wagle et al. 2022). Although the long-term benefits of ECT have yet to be fully examined, Benjamin et al. (2013) found that production costs were relatively consistent with other harvesting operations in part due to high machine productivity, while increased biomass production was achieved when a whole-tree harvester system was utilized and could be a viable option if consistent biomass markets were available.

In terms of carbon, PCT and ECT are expected to have positive effects on both sequestration and long-term storage. Both methods effectively increase both tree- and stand-level growth, while positively shifting volume toward longer-lived forest products like sawlogs. By effectively shortening rotations, additional storage capture can be achieved with the establishment of young and highly productive stands, particularly plantations of fast-growing species like spruce or white pine. Continued monitoring of long-term research installations where PCT or ECT has been applied is recommended while exploring potential market or policy incentives for implementations should be explored.

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Appendix C: UMaine Modeling Report

UMaine and USDA Forest Service Data and Modeling Details for the Forest Carbon for Commercial Landowners Project | By Adam Daigneault, Erin Simons-Legaard, Jeanette Allogio, Laura Kenefic, Aaron Weiskittel, and Zoë Lidstrom

Overview

Maine's policy makers and landowners are considering initiatives to incentivize forest management in ways that would enhance terrestrial and harvested wood product (HWP) carbon sequestration and thereby help meet climate change mitigation targets. While forests are expected to play an important role in meeting the state's climate mitigation target, stakeholders are concerned about how Maine's forests can increase carbon storage while also meeting other objectives (e.g., consistent timber supplies, other ecosystem services objectives). The degree to which these multiple objectives can be met is currently unknown, especially with respect to potential actions by Maine's large landowners who supply the bulk of the timber harvests and conduct most of Maine's active forest management. In this context, the Forest Carbon for Commercial Landowners (FCCL) initiative has suggested the necessity of research to answer the following questions:

- Can large commercial forests in Maine be managed to sequester and store more carbon and maintain harvests?
- What is stopping landowners from sequestering and storing more carbon today?
- What mechanisms or policy instruments could be put in place to incentivize forest management that will sequester and store more carbon?
- What are the longer-term benefits of jointly focusing on forest carbon and timber harvests to Maine?

In response, the FCCL Technical Committee proposed research that applied the following approach to address these questions: (a) use an existing dynamic landscape model of northern Maine (LANDIS-NM) to analyze forest ecosystem dynamics and harvest levels under different silvicultural systems designed to increase forest and HWP carbon, (b) link the forest landscape model outputs with economic data in an integrated model framework to evaluate the impacts of alternative silvicultural systems on harvests, landowner revenue, and carbon in forests and HWPs, (c) use a scenario-based approach to analyze how alternative silvicultural systems might alter the ability of Maine's forests to store carbon over the next 50 years under a range of different socioeconomic and policy conditions or constraints, and (d) use the model to identify cost-effective and efficient opportunities, including potential practice-based incentives, that could be implemented to achieve greater carbon sequestration and storage while maintaining timber harvests in Maine. This modeling framework and analysis was developed through eight separate but integrated tasks:

Task 1: Develop conceptual framework for project.

Task 2: Review forest management prescriptions and select silvicultural systems for modeling.

Task 3: Assemble the necessary economic inputs for the model.

Task 4: Develop, implement, and test the model.

Task 5: Conduct analysis for baseline and alternative future scenarios.

Task 6: Analyze effects of alternative carbon pricing and practice-based incentives.

Task 7: Perform more detailed case-study assessments.

Task 8: Prepare summary white paper and compile technical appendices.

The organization of these tasks are presented in Figure 1. This report provides details on aspects of Tasks 1–5 related to the forest landscape and economic modeling components of FCCL. Details related to other tasks—as well as the overall findings of the study—are included in the FCCL project white paper (Task 8).[1]

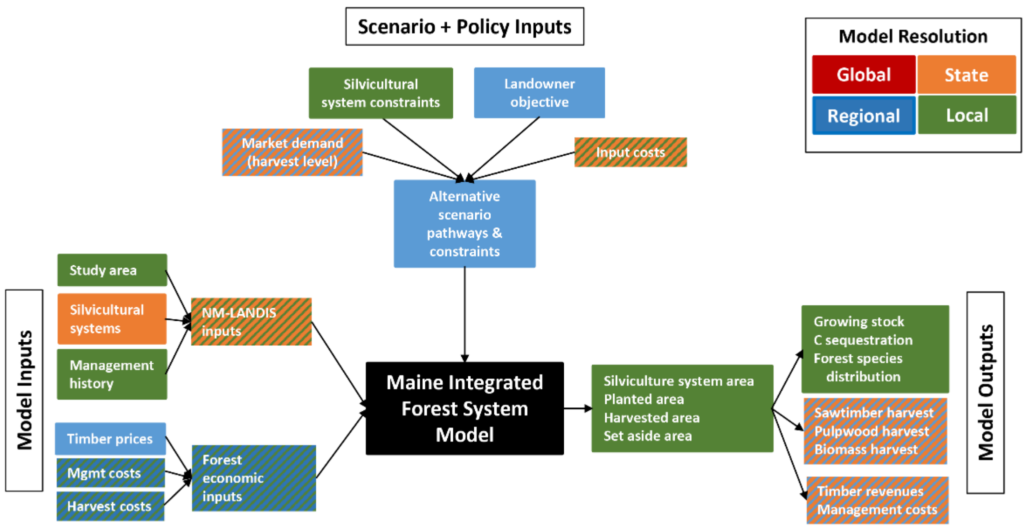

Figure 1. Forest Carbon for Commercial Landowners (FCCL) Model and Work Plan Schematic

Conceptual FCCL Model

University of Maine researchers have developed the Maine Integrated Forest System Model (MIFSM) to systematically evaluate potential impacts from implementing different forest management options across Maine's working forests. The decision support tool is designed to link 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 socioeconomic futures, thereby allowing one to better understand the various trade-offs that could emerge as a result. The MIFSM is based on a modeling framework that has been used to conduct regional, national, and global analyses (Daigneault and Favero 2021; Daigneault,

[1] Task 7 was adjusted as the project progressed, and the focus shifted toward conducting sensitivity analysis for the entire project area.

Greenhalgh, and Samarasignhe 2018; Ausseil et al. 2019). The FCCL project extended this framework to create a tool that combines a forest landscape (LANDIS-NM) with economic data and policy inputs into an optimization model framework to specifically quantify impacts across northern Maine's diverse forest landscape (Figure 2). MIFSM can be used to ask questions such as, "What is the impact of implementing a specific management practice on Maine's forest carbon stocks and timber output?" or, "What mix of practices needs to be employed across Maine's working forests to increase Maine's forest carbon while also maintaining or enhancing annual timber supply?" The integrated model was parameterized for the FCCL project to answer these questions for a set of user-based model assumptions by selecting the optimal mix of practices and harvest schedules to employ across the landscape to meet a specified objective (i.e., maximize net revenue or total carbon sequestration subject to meeting annual harvest targets). More details on how this conceptual model was parameterized and utilized are explained below.

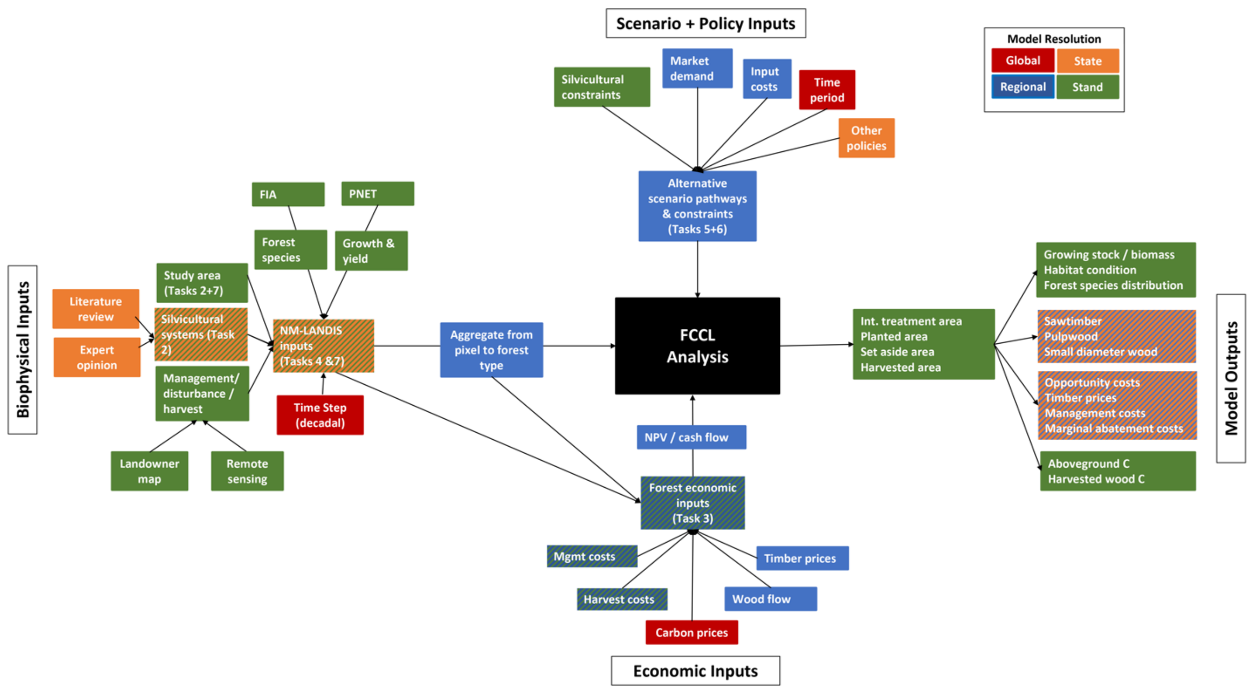

Figure 2. FCCL Conceptual Model Framework

Reviewing Silvicultural Systems for the Modeling and Evaluation of Carbon-Smart Silviculture

The USFS, with input from UMaine and the FCCL technical team, led a review of the research literature and consulted with silvicultural experts to select a portfolio of silvicultural systems for how commercial timberland owners in Maine might change their land management practices to sequester and store more carbon. The review consisted of about 20 papers that were supplied to the USFS by collaborators or found through a search of the literature (see Appendix A). The results and most useful take-home messages of these papers have been summarized in a project spreadsheet. Many studies consider the effects of silvicultural practices on carbon stocks in the forests of Maine, while other papers look at related topics such as soil compaction and greenhouse gas emissions.[2]

Several common themes emerged while synthesizing these data, and we will summarize some of these here. Unmanaged stands tend to store more total ecosystem carbon than harvested stands, causing researchers to recommend the incorporation of unharvested reserves in forest management plans. However, researchers are generally optimistic that certain management practices can balance meaningful carbon storage or sequestration while conferring other benefits including commercial harvesting. For example, several studies showed that uneven-aged structure and increased structural complexity were associated with greater carbon stocks. All studies that considered clearcut harvests found that naturally regenerated clearcut stands stored less carbon than stands undergoing other treatments. Selection silviculture, in particular, has been shown repeatedly to favor carbon storage, as have decreased harvesting frequency and greater residual basal area. Harvesting for wood energy has shown varying results.

Key knowledge gaps that have been identified by this synthesis included the lack of studies examining planted stand dynamics and the primary focus on stand- rather landscape-level analyses. The few studies that have evaluated planted stands with both native and exotic species in this region have shown high productivity, yet long-term observations are limited. At the landscape level, a mix of management approaches with strategic set-asides has been shown to be most beneficial in both the short- and long-term time horizons. We also note that not all of the studies included estimates on impacts of treatment on harvest levels or quality. As a result, it may be difficult to make direct comparisons to the results of the FCCL study.

Based on these insights and others gathered from conversations with silvicultural experts, the FCCL technical team selected seven silvicultural systems/treatments for inclusion in the analyses (Table 1):

- **Partial Harvest (Business as Usual):[3]** A non-selective, moderate harvest option with no explicit stand regeneration objectives. This is designed to approximate average harvest practices across Maine's commercial timber landscape in recent decades (Legaard, Sader, and Simons-Legaard 2015; Simons-Legaard, Legaard, and Weiskittel 2021). Removals of 50 percent of standing volume are carried out on a 50-year cycle.
- **Continuous Cover:** commercial thinning/establishment cuts repeated at 30-year intervals with 35 percent of the standing volume removed. Results in uneven-aged stands continuously harvested.
- **Regular Shelterwood:** Initial establishment cut removing 60 percent of standing timber volume followed at year 10 by removal of remaining overstory. Pre-commercial thinning 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.
- **Irregular Gap:** Small gaps with 100-percent removal created in forest matrix on a 20-year cycle. Gaps cleaned on a 20-year cycle after creation. Areas between gaps commercially thinned on a 20-year cycle. Results in uneven-aged stands that are continuously harvested.

[2] N.B., a similar literature review was also conducted as part of the Maine Governor's Forest Carbon Task Force (2021). The data and sources from that literature review can be found here.

[3] This project's initial modeled business-as-usual (BAU) scenario assumed that the entire landscape consisted of partial harvesting. As a result, any reference in this report to BAU is equivalent to the partial harvesting practice until the "Alternative Future" scenarios and results sections.

- **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.
- **Clearcut and Plant**: Initial removal of 100 percent of standing timber volume. Regeneration relies on planting. Competition from undesirable species is managed with herbicides. Commercial thinning at year 25. This results in an even-aged stand that is expected to be ready for harvest at year 50.
- **Set Aside and Unharvested:** areas designated as not cut nor managed. These can include conservation areas with deeded harvest restrictions and other inaccessible forests within the study area (e.g., stands with steep slopes), or areas eligible to be harvested but that the model has opted not to manage or cut during the 60-year modeled period.

Table 1. Overview of FCCL Modeled Silvicultural Systems

System	Description	Treatment 1	Treatment 2	Treatment 3	Treatment 4	Treatment 5	Treatment 6	Treatment 7
BAU (Partial Harvest)	Non-system moderate harvest, non-selective	Harvest @yr 0, 50% removal	Harvest @yr 50, 50% removal					
Cont_Cover	Continuous cover irregular shelterwood	CT/Estab. cut @yr 0, 35% removal	CT/Estab. cut @yr 30, 35% removal	CT/Estab. cut @yr 60, 35% removal				
RegShelt	Regular shelterwood, typical rotation	Estab. cut @yr 0, 60% removal	OSR @yr 10, 100% removal	PCT @yr 25, favoring spruce	CT @yr 40, 35% removal	Estab. cut @yr 60, 60% removal, prioritizing fir		
Irr_Gap	Gap irregular shelterwood	CT/Estab. cut @yr 0, 100% removal gaps (20% of area), 20% removal matrix, combined low and crown thinning	Cleaning in gaps @year 15	CT/Estab. cut @yr 20, 100% removal gaps (20% of area)	Cleaning or CT in gaps @year 35, 35% removal, combined low and crown thinning	CT/Estab. cut @yr 40, 100% removal gaps (20% of area)	Cleaning or CT in gaps @year 55, 35% removal, combined low and crown thinning	CT/Estab. cut @yr 60, 100% removal gaps (20% of area)
CC_Plt	Clearcut, plant native	100% removal @yr 0, herbicide, spruce	CT @yr 25, 35% removal	100% removal @yr 50, herbicide, plant spruce				
CC_Nat	Clearcut, natural regeneration	100% removal @yr 0, naturally regenerate	100% removal @yr 50, naturally regenerate					
No_Harvest	No harvest / set aside reserves	No harvest or management for duration						

Maine Forest Economic Data

Task 3 of the FCCL project was to assemble the economic and financial data for the forest management and harvest practices listed in Table 1. Key revenues and costs include:

- Delivered log and stumpage prices by species and product (saw, pulp, biomass)
- Site prep cost
- Intermediate treatment cost
- Harvest cost
- Hauling/transport costs

Data were obtained from a number of sources, which are listed in the references section of this report. We split our findings into "silvicultural treatment costs" (costs of performing intermediate treatments toward specific silvicultural goals) and "logging costs" (costs performed while conducting final harvests). In many cases, researchers presented costs on a dollar-per-acre basis, but in some cases our team had to convert to dollars per acre from other units or currencies. Some of the key findings are summarized below.

Stumpage and Delivered Log Prices

The Maine Forest Service publishes annual stumpage price reports based on data provided by landowners from all over the state. A summary of the variation in prices for key products is shown in Figure 3. The products of most importance to the FCCL study are biomass, pulpwood, and sawlogs, as this is the detail of harvests output reported by LANDIS-NM. Based on the last five years of available data (2015–2019), these three products respectively averaged $1.90/green ton, $7.80/green ton, and $152.90/thousand board feet (approx. $30.60/green ton).

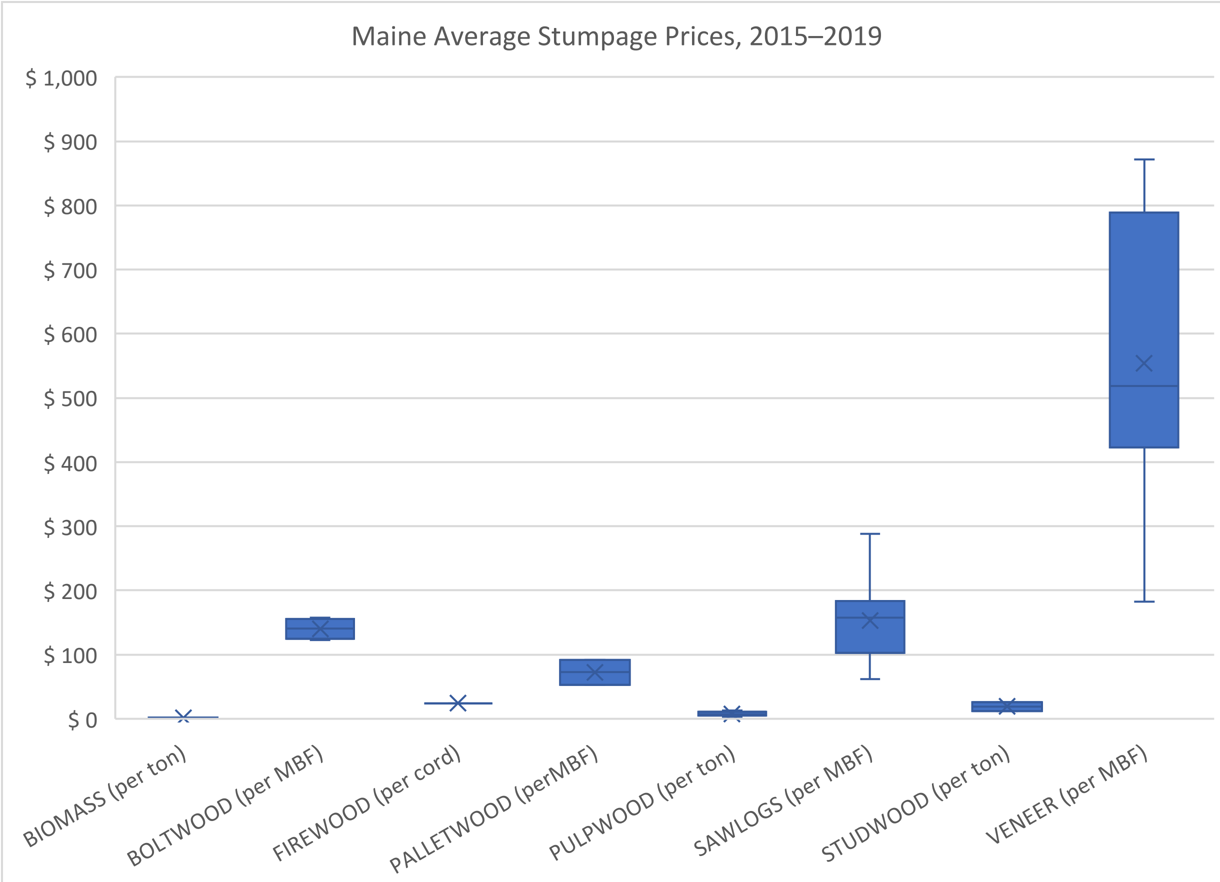

Figure 3. Maine All-County Average Mean Stumpage Prices by Product, 2015–2019
(Variation in each box plot is across commercial species)

Less publicly available data is available for delivered log prices. As a result, we relied on Stevens's (2018) summary of historical trends from 2013 to 2017 (Table 2). Note that, given the structure of our model and focus on quantifying the costs of different silvicultural treatments, we used log delivered prices in our analysis.

Table 2. Maine Historical Log Delivered Prices ($/Green Ton) Based on Stevens (2018)

Log Type	Min	Max	Steady-state
Hardwood pulpwood	$44	$57	$50
Spruce-fir pulpwood	$37	$54	$38
Other softwood pulpwood	$34	$48	$36
Spruce-fir sawable (non-logs)	$55	$77	$64
Hardwood grade logs	$84	$104	$94
Hardwood pallet logs	$67	$75	$71
Pine logs (all grades)	$84	$101	$93
Biomass	$25	$41	$30

Silvicultural costs

For silviculture costs, the NRCS cost-share program (Natural Resources Conservation Service 2021) estimates the cost of an exhaustive list of preparatory and intermediate treatments including brush management, competition control, thinning, crop tree release, small patch clearcuts, pre-commercial thinning, site preparation, and planting. Each total cost estimate includes hourly labor costs, machine mobilization and utilization costs, and a representative area across which the treatment would be applied. Costs ranged widely across practices from under $100 per acre for certain brush management or site preparation practices to over $1,000 for treatments or harvests involving pole-size or larger trees. All NRCS cost estimates may be found in the Appendix.

Kenefic et al. (2014) examined the cost of rehabilitating cut-over northern conifer stands in Maine using a combination of manual (chainsaw) and herbicidal (triclopyr) treatments. They compared moderate rehabilitation (crop tree release) and intensive rehabilitation (crop tree release, timber stand improvement, and fill planting) to a no-treatment control to ascertain cost-effectiveness. They calculated the amount of time needed for these two treatments and then derived per-acre costs that included fixed labor costs ($/hour), herbicide costs ($/gallon), and fuel costs ($/gallon). Total costs ranged from $380 to $795 per acre. Similarly, Bailey, Saunders, and Lowe (2011) calculated a range of dollar-per-acre costs associated with mid-story removals in Indiana that included some combination of manual (chainsaw and brush saw), mechanical (tree mower), and herbicidal (triclocpyr and imazapyr) treatments. Their estimates included fixed rates for labor ($/hour), herbicide ($/gallon), fuel ($/gallon), and equipment rentals ($/day), and for each treatment, they estimated the low cost and the high cost of treatment based on time spent and herbicide and fuel used. Total costs ranged from $68 to $258 per acre.

The Northern Hardwoods Research Institute issued a bulletin (2017) presenting the per-area costs of thinning in even-aged tolerant hardwood stands in New Brunswick. All harvests were cut to length and involved a harvester. Costs differed based on the intensity of thinning, which ranged from the Q-line ("stocking level suggested to ensure the natural shedding of live branches") to the B-line ("the lower limit of stocking needed for full occupancy of the site"), and finally to the C-line (the "stocking level that is expected to reach B level within 10 years"). Total costs ranged from $107 to $129 per acre (U.S. dollars converted from Canadian dollars).

Hiesl et al.'s studies (2015, 2016) concerned commercial thinnings in northern conifer stands in Maine. The 2015 paper compared the cost of commercial thinning in a stand that had previously undergone pre-commercial thinning (PCT) to the cost of commercial thinning in a stand that had not undergone PCT. The PCT stands were harvested using a harvester, while the non-PCT stands were harvested with a feller-buncher. The 2016 paper compiled harvest costs as part of a long-term study on the effects of commercial thinning on net present value of stands. Commercial thinnings in this study were conducted with a harvester using a cut-to-length system. Total costs in both studies were presented as dollars per productive machine hour (PMH), which our team was able to convert to dollars per acre using Hiesl et al.'s (2015) estimates for the number of PMH per acre. Note that these values include only the cost of felling logs (not bringing them to the landing). Costs ranged from $247 to $824 per acre for both studies.

Daigneault et al. (2021) developed an estimate for planting costs in Maine assuming seedlings ($0.37/plant) planted at a density of 800 trees per acre ($296/acre) and site prep that included two spray applications ($250/acre), for a total of $546/acre.

The FCCL team visited harvest sites in fall 2021, where representatives of commercial forest companies presented estimates of current per-acre costs of pre-commercial thinning, ranging from $275 to $325 per acre, noting this is a recent increase from historical trends ranging from $100 to $150/acre.

All of the silviculture cost data estimates are summarized in Figure 4. Apparent in the figure is that there is wide variation in costs for many of the treatments. Some of this can be attributed to data from NRCS and other sources focused on treatments conducted on small landholdings. As a result, we typically used the lower estimates in this study, as those are likely to be more indicative of costs faced by large landowners.

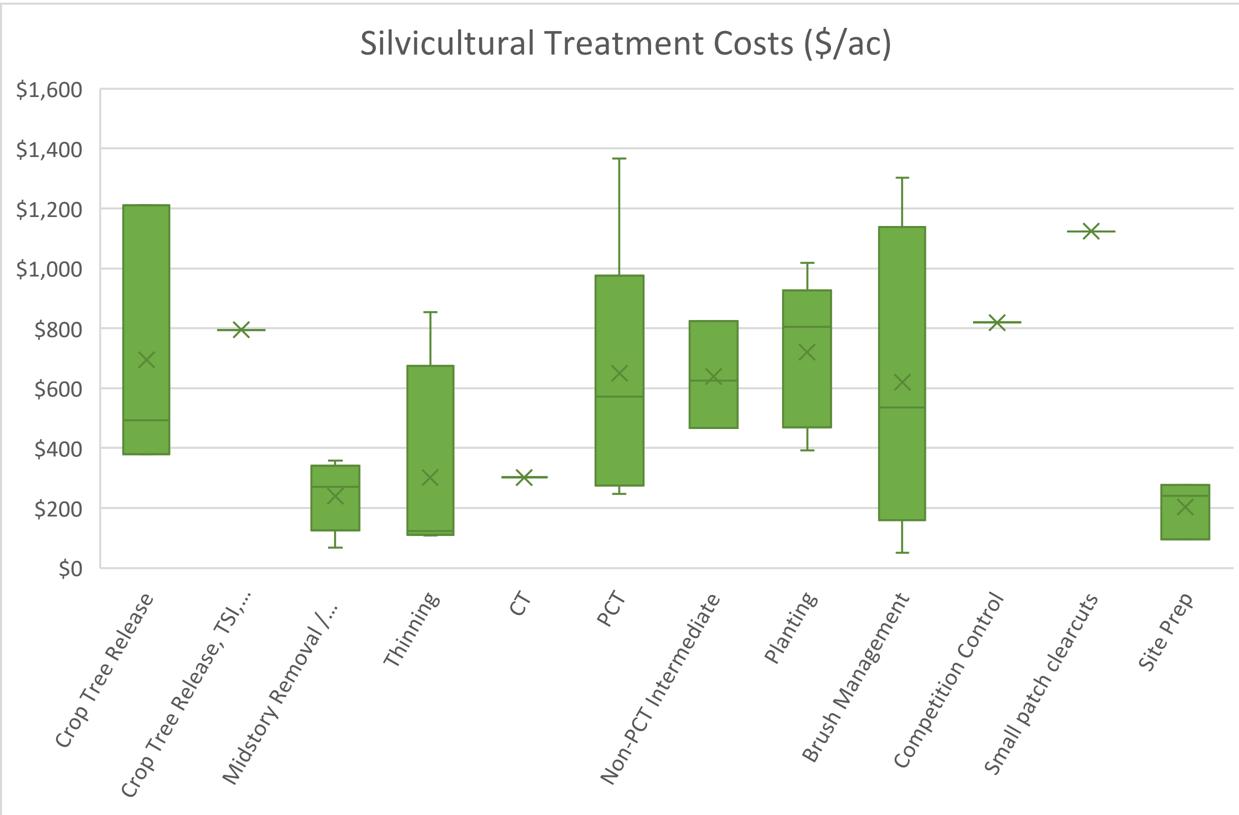

Figure 4. Silvicultural Treatment Cost Data Estimates Based on Literature Review

Logging costs

Soman, Kizha, and Roth (2019) examined the costs of partial harvests and clearcuts in Maine, both of which were conducted using a feller-buncher. Their partial harvest analysis included a diameter-limit cut and a crop tree release, from which they modeled the cost of partial harvests more generally. Similarly, their clearcut analysis included an overstory removal of all trees at least 13 centimeters in diameter at breast height and a logging clearcut that removed all trees at least five inches in diameter at breast height, from which they modeled the cost of clearcuts in general. Harvests were conducted with a feller-buncher. Harvesting costs, which included felling, skidding, and landing logs, were calculated in dollars per cubic meter, a number our team converted to dollars per acre. Costs ranged from $412 to $1,356 per acre.

Germain et al. (2019), in their analysis examining several independent variables for their effect on per-unit general logging costs, calculated total cost and total land area harvested at about 25 sites of various size and with varying silvicultural prescriptions, crew sizes, and harvest systems. Harvests were located in New York and northern Pennsylvania. Our team took the highest and lowest of the 25 per-unit logging costs from this study to project a range of costs. The study reported the cost of logging in dollars per hectare, which we translated to acres, and ranged from $197 to $520 per acre. A summary of results from this study are presented in Figure 5.

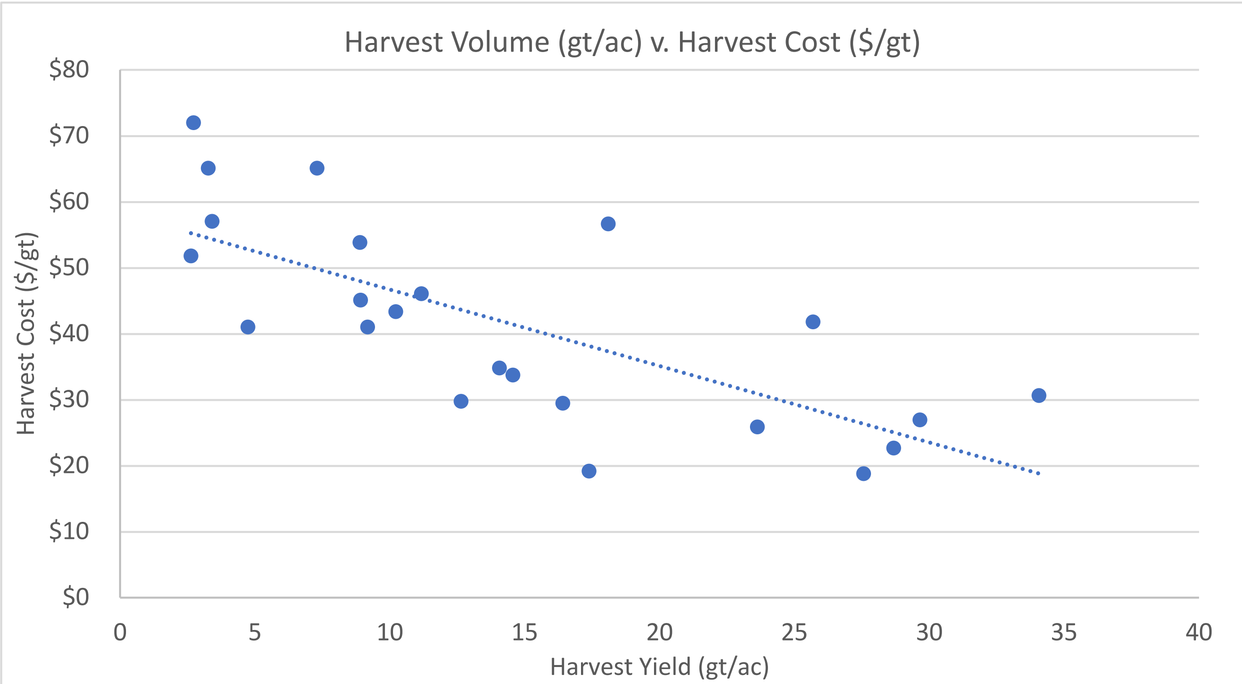

Figure 5. Harvest Cost Variation by Harvest Volume, from Germain et al. (2019)

Buchholz, Keeton, and Gunn (2019) calculated the costs of biomass removal for biomass chips and biomass logs in Vermont, New Hampshire, and New York. Their calculated costs included stumpage and machine mobilization costs as well as logging, chipping, and/or landing costs. Biomass destined to be chipped was harvested using a whole-tree (WT) method, while biomass logs were harvested using non-WT methods. Thus, chipping costs were included for WT harvests while non-WT harvests included landing costs. They reported their cost values as dollars per green ton. Our team then converted these values to dollars per acre using their reported average harvest of 19.4 green tons per acre. Costs ranged from $408 to $564 per acre.

A summary of logging costs from our literature review is shown in Figure 6. The figure highlights that there is less variation in costs compared to the silvicultural treatments, however this can largely be attributed to a smaller set of studies and observations collected.

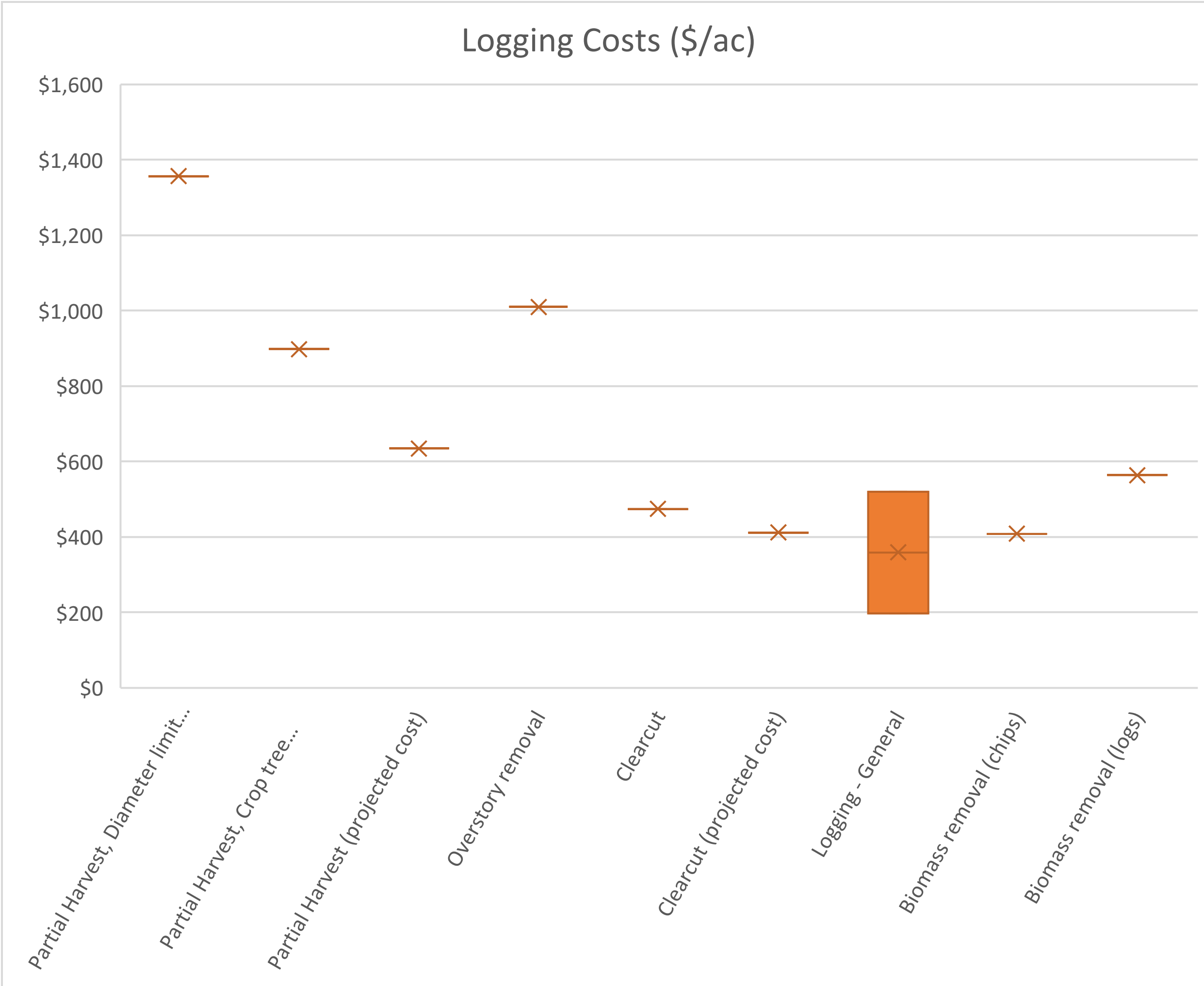

Figure 6. Logging Treatment Cost Data Estimates Based on Literature Review

Hauling / Transport costs

Logging and transport costs can vary by distance and truck capacity. For this study, we used info from Hiesl (2015) and Koriala, Kizha, and De Urioste-Stone (2017), and reported in AECOM (2020) to quantify the mean distance and hauling capacity of Maine's logging transportation network (Figure 7). On average, it is reported that Maine logging trucks travel 133 miles per haul, with 45 percent of the trip (60 miles) spent fully loaded, and have a loaded capacity of 30 tons of logs or chips, which equates to a cost of $16.32/green ton when the cost of fuel is $4/gallon.

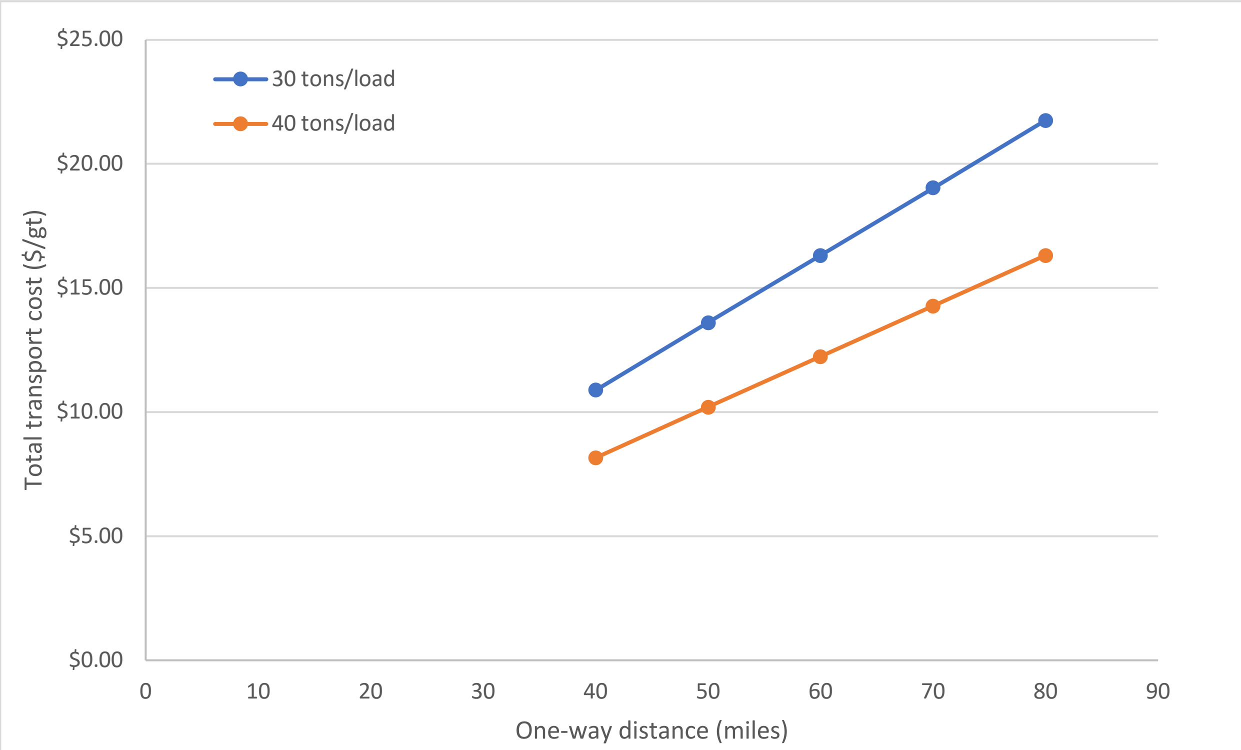

Figure 7. Maine Log Transport Cost by Distance and Truck Capacity

FCCL Modeling Approach

The FCCL modeling used an integrated approach that linked estimates from a forest landscape model (NM-LANDIS) 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 outlines the key approaches and results associated with the modeling exercise. We start with describing NM-LANDIS model and output, followed by the integrated optimization modeling approach and estimates.

NM-LANDIS Model Overview

Forest landscape models (FLMs) have become an essential tool for predicting the broad-scale effects of anthropogenic and natural disturbances on forested landscapes. One open-source FLM that has become widely used to compare alternative future scenarios across large areas is the LANDscape DIsturbance and Succession (LANDIS) model (Gustafson et al. 2000, Mladenoff 2004, Scheller et al. 2007). First released in the mid-1990s, LANDIS was designed to stochastically simulate the spatiotemporal effects of repeated interactions between forest disturbance and succession based on a moderate number of user-specified parameters (Mladenoff et al. 1996, Mladenoff and He 1999). Since its release, LANDIS or the updated version, LANDIS-II, has 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.

Within LANDIS-II, the forest is represented by a raster grid of interacting cells, aggregated by user-defined ecoregions (homogeneous soils and climate). Successional processes including tree establishment, growth, competition, and mortality are modeled for each cohort (i.e., group of trees defined by species and age) in each cell, and 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. Cells are modeled as spatial objects linked by the processes of seed dispersal, natural disturbance, and land use. Execution of LANDIS-II requires the parameterization of tree species' life history attributes, specification and parameterization of key ecological processes, and spatial representations of initial forest and landscape conditions.

For this study we used a customized version of LANDIS-II to model the effects of alternative silvicultural treatment strategies on the carbon and harvest dynamics of more than 7.5 million acres of forested area in northern Maine (NM-LANDIS) from 2010 to 2070. This version of the model tracks impacts to Maine's 13 most abundant tree species, comprising 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 Forest Inventory and Analysis (FIA) plot data and Landsat satellite imagery.[4] Our study area (Figure 8) encompassed approximately 9 million acres, of which 7.5 million acres was forestland. Owners within this area are predominantly considered large landowners (>10,000 acres) and represent a diverse range of ownership types (e.g., family, high-net-worth individuals, timber investment management organizations, real estate investment trusts, and nonprofit organizations).

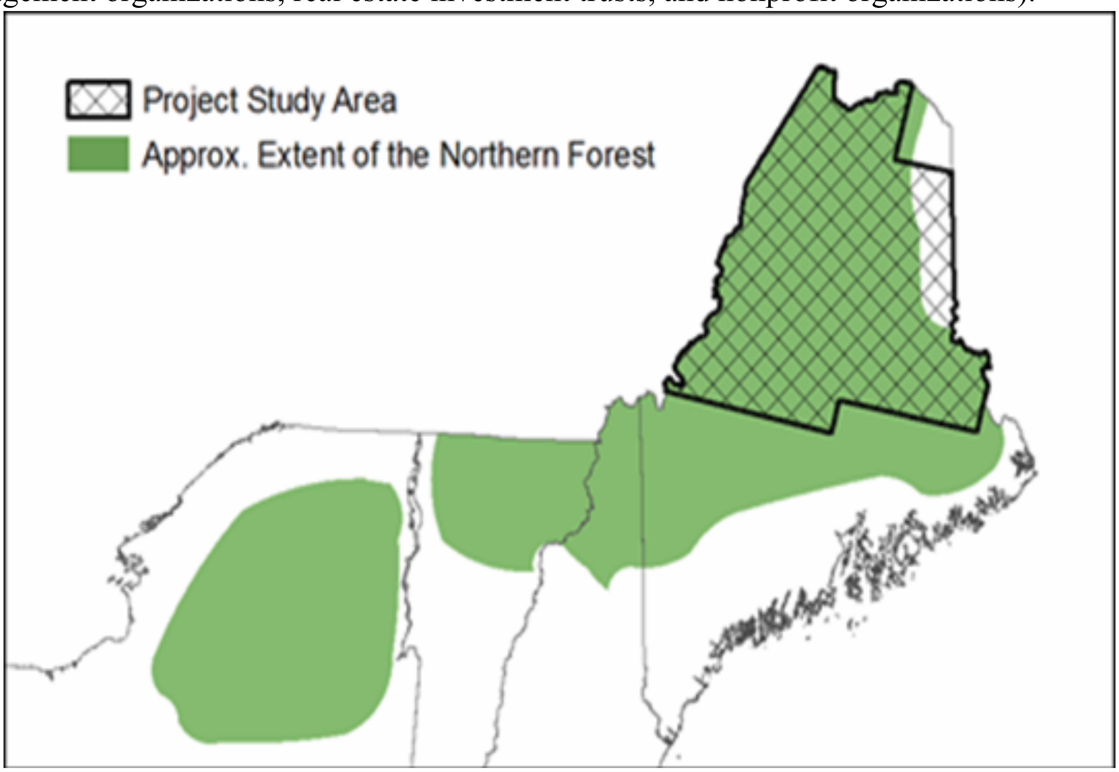

Figure 8. FCCL Model Study Area. *The project study area for forest landscape projections using LANDIS-II encompassed approximately 7.5 million acres of predominantly commercial forestland across approximately 9.1 million acres of land in northern Maine.*

The LANDIS-II model consists of a core program and user-selected modules that have been developed to simulate succession and a variety of disturbance agents. We used the Biomass

[4] Following the methods of Legaard, Simons-Legaard, and Weiskittel 2020.

Succession 5.3.1 module (Scheller and Mladenoff 2004) to model forest growth and succession, the Base Wind 3.1 module (Scheller et al. 2007) to model blowdown, and the HARVEST 4.4 module (Gustafson et al. 2000) to model timber harvesting. The impacts of climate change on species establishment and growth were modeled using outputs from the process-based PnET-II model (Aber et al. 1995) in a manner similar to previous LANDIS-II studies (e.g., Ravenscroft et al. 2010). PnET-II predicts monthly changes in photosynthesis and the production of biomass (foliar, wood, root) using species-specific traits (e.g., foliar nitrogen) and climate inputs, including average minimum/maximum surface temperature and total monthly precipitation. For this study, we used historical average climate data (i.e., assume no climate change). While potentially a limitation, estimates from Daigneault et al. (2021) suggest that climate impacts have a small impact on overall growth and yield across our study time frame (i.e., to 2070).

Over the course of a simulation, NM-LANDIS tracks aboveground biomass for each cohort in each cell, along with species and age information, and reports the results at a user-specified interval. We ran NM-LANDIS at a 10-year time step and calculated (1) total and per-species aboveground carbon and (2) total and per-species harvested carbon at the end of each interval (e.g., 2010–2020, 2020–2030, etc.) for each forest treatment or alternative future scenario. Growing stock and harvest levels were further disaggregated into biomass/pulp and sawlog grade quality using the assumption that any cohort less than 40 years of age fell into biomass/pulp while anything 40 years or more fell into sawlogs, which resulted in estimates that aligned closely with harvest levels reported by the Maine Forest Service.[5]

As NM-LANDIS is an area-based model, the user must specify the amount of area to be harvested each period. This creates a limitation for our study, which emphasizes holding harvests constant at historical levels over time. As a result, the default NM-LANDIS output is unable to meet this specific criterion, even with multiple iterations of changing the treatment area under consideration. Further, while one can provide the specific amount of area to be treated in NM-LANDIS for each decade, in most cases the total area eligible to meet that criterion (e.g., partial = remove 50 percent of biomass from stands 50 years or older) exceeds the target area (e.g., 150,000 acres/year). This thus results in some stands being treated/harvested in later periods than when they are considered eligible. This limitation also makes it difficult to compare impacts across treatments on a decade-by-decade basis. As a result, we use the average NM-LANDIS outputs across the 2010–2070 simulation to parameterize the forest growth, yield, and harvest aspects of the MIFSM optimization model.

NM-LANDIS estimates aboveground (AG) and removed/harvested carbon stock by decade for 13 species and two timber types (pulp and sawlogs). We convert removed carbon to that stored in harvested wood products (HWPs) to account for the long-term "decay" in these products (i.e., not "permanently" stored in products or landfills). Based on Smith et al. (2006), we assume that 10 percent of pulp and biomass harvests are stored in HWPs, while 40 percent of sawlogs are stored. We then use these combined estimates for AG and HWP carbon to quantify the total annual carbon sequestration for different forest types, treatments, and scenarios by annualizing the decadal change in total carbon stock (i.e., annual flux).

Overall NM-LANDIS Results

The key outputs of interest from NM-LANDIS, broken out by silvicultural system, are shown in Figure 9. Note that these outputs are adjusted such that the mean annual harvest between 2020

[5] https://www.maine.gov/dacf/mfs/publications/annual_reports.html

and 2070 is constant across all treatments. The results highlight how there is noticeable variation both within and across treatments, despite the total annual harvests equating to 2 million metric tons of carbon per year (MtC/y).

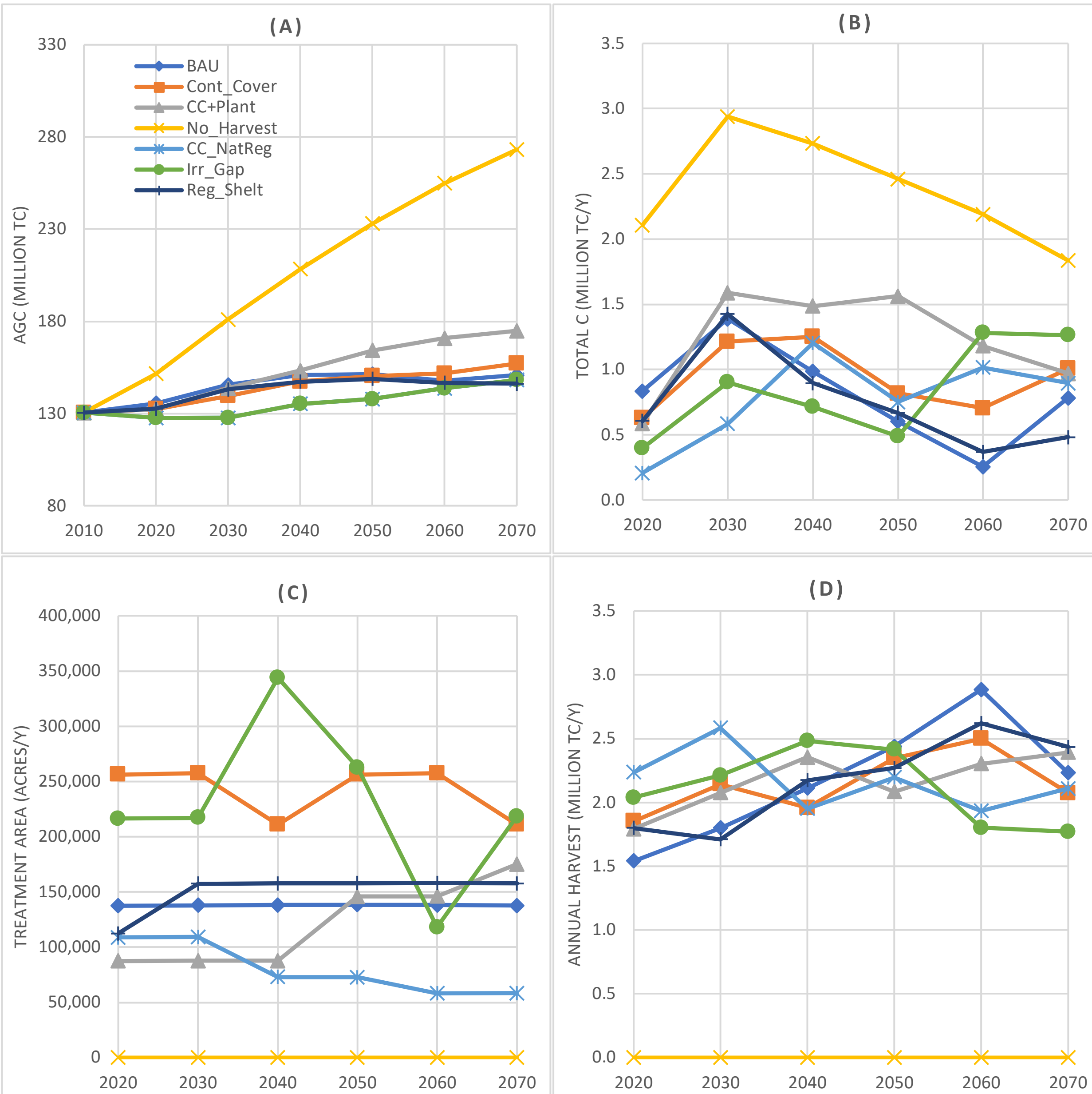

Figure 9. NM-LANDIS Estimates for (a) Aboveground Carbon Stock, (b) Annual Total (Aboveground and HWP) Carbon Sequestration, (c) Silvicultural Treatment Area, and (d) Annual Harvest Amount by Silvicultural Treatment

Forest Type Aggregation

The NM-LANDIS model is parameterized at a 30 x 30-meter-per-pixel resolution. While this high-resolution approach is good for modeling forest dynamics across the landscape, the amount of output data that is created makes it difficult to directly incorporate into an integrated model for optimization and scenario analysis. As a result, we consulted with the FCCL tech team to determine an aggregation that makes it computationally possible to run the optimization model and still provide enough detail for useful comparison across treatments and scenarios. This compromise resulted in aggregating NM-LANDIS pixels into 108 unique forest type combinations that were based on species type, land productivity, and mean initial stand age and density. The criteria used to aggregate the forest types are listed in Table 3, while the spatial pattern of these forest type combinations is shown in Figure 10.

Table 3. FCCL Forest Type Combination Aggregation Criteria

Species (Raster Class)	Site Productivity (BGI, kg/ha/y)	Initial Biomass Density (gC/m2)	Initial Age
Spruce-Fir (1-18)	Low (< 2500)	Low (<3000)	< 40 years
Eastern White Pine (19-36)	Medium (2500-4000)	Medium (3000-5000)	> 40 years
Other Softwood (37-54)	High (>4000)	High (>5000)	
Other Hardwood (55-72)			
Beech (73-90)			
Mixedwood (91-108)			

These combinations were then used to define “sideboards,” or constraints on where specific silvicultural treatments could be undertaken in the analysis, as defined by the FCCL tech team. For example, it was determined that clearcut-and-plant systems could only take place on high-productivity sites that had a biomass growth index (BGI) of 4,000 kilograms per hectare per year of growth or higher. A summary of these criteria and the eligible area for each are listed in Table 4. This approach indicated that 92 percent or more of the 7.5 million acres of forested area was eligible for six of the seven modeled treatments, excluding the clearcut-and-plant system, which was restricted to 5.5 million acres (73 percent total area).

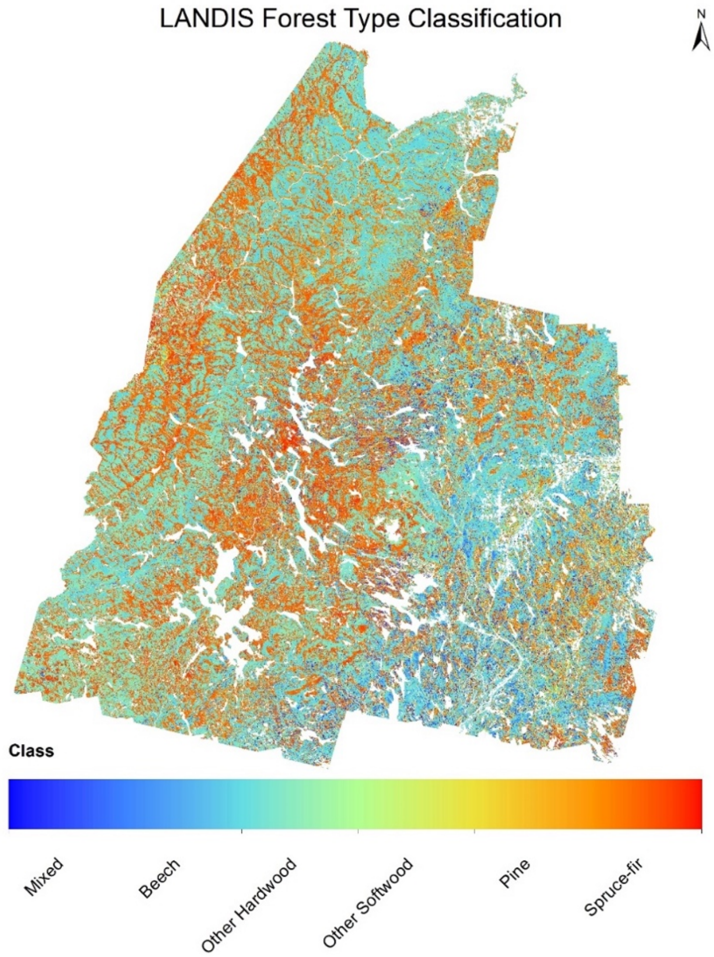

Figure 10. 108 Forest Type Combination Aggregation for FCCL Scenario Analysis

Table 4. FCCL Criteria for Eligible Silvicultural Treatments by Forest Type

Treatment	Eligible Forest Types	Site Productivity	Other Considerations (Cannot necessarily be modeled)	Eligible Area (acres)
Partial Harvest (BAU)	Spruce-Fir Eastern White Pine Other Softwood Beech Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	50% removal, all species treated equally	7,583,005
Clearcut and Plant	Spruce-Fir Eastern White Pine Other Softwood Beech Other Hardwood Mixedwood	High (>4000)	Thin: 60 years No Thin: 50 years Target sites w/ low value hardwoods or fir Could consider extending rotation to 70-80 years for max MAI	5,535,602
Clearcut + Natural Regenerate	Spruce-Fir Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	Low prospect of spruce if no advance regeneration Hardwood stands might have lower timber quality/value than SF, but maybe okay for Carbon. If low value species regenerate, consider planting option instead	7,010,278
Continuous Cover	Spruce-Fir Eastern White Pine Other Softwood Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	Stands which are overstocked with trees with small tops (<30-40% live crown) should be either thinned very lightly or left untreated, particularly on sites prone to windthrow. Softwood stands with PCT can receive ECT at age 25-30.	7,583,005
Regular Shelterwood	Spruce-Fir Eastern White Pine Other Softwood Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	Softwoods: Same specifications for harvest as clearcut with natural regeneration Hardwoods: harvest at 60 if thinned, 80 if not	7,445,773
Irregular Shelterwood (Exemplary forestry)	Spruce-Fir Eastern White Pine Other Softwood Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	Gaps likely created for stands 50-60+ years old Thinning: same as for continuous cover	7,445,773
No Harvest / Set Aside	Spruce-Fir Eastern White Pine Other Softwood Beech Other Hardwood Mixedwood	Low (< 2500) Medium (2500-4000) High (>4000)	No management or harvest (i.e., permanently set aside)	7,583,005

Reviewing the NM-LANDIS output at forest type combination level reveals some interesting findings. As one of the key concerns is to evaluate how to increase total carbon sequestration while holding harvests constant over time, we can plot the annual rates of these two metrics by forest combo and treatment (Figure 11). A few interesting things emerge in this figure. First, there are several business-as-usual partial harvest (BAU) plots that have relatively low harvest rates, which result in fairly high sequestration rates relative to other practices. On the other end, the regular shelterwood and clearcut with natural regeneration plots have much higher harvest rates, which result in lower carbon sequestration. Second, the plots of carbon versus harvest rates are noticeably different for the clearcut-and-plant treatment, showing greater carbon sequestration than most of the other silvicultural treatments. This makes sense because the planting aspect of this practice encourages faster growth and yield than the other cases, thereby resulting in more carbon in standing biomass while still allowing intensive harvests to simultaneously occur across the landscape. Second, we note that the rates can vary across the same forest type combination (which can be seen to some degree here by the size of potential area that a practice can be undertaken in), highlighting both the potential for some plots to be more advantageous than others to meet specific objectives, as well as the potential randomness that can emerge from the NM-LANDIS approach (as not every forest type combo is necessarily accessed and harvested the same period for each treatment/scenario).

Breaking out harvests by wood product type (pulp/biomass and sawlog) reveals similar trends, although with more variation than the total harvest plot (Figure 12). This is because different treatments result in different levels of product harvests, particularly based on the way that NM-LANDIS specifies product output (+/- 40 years).

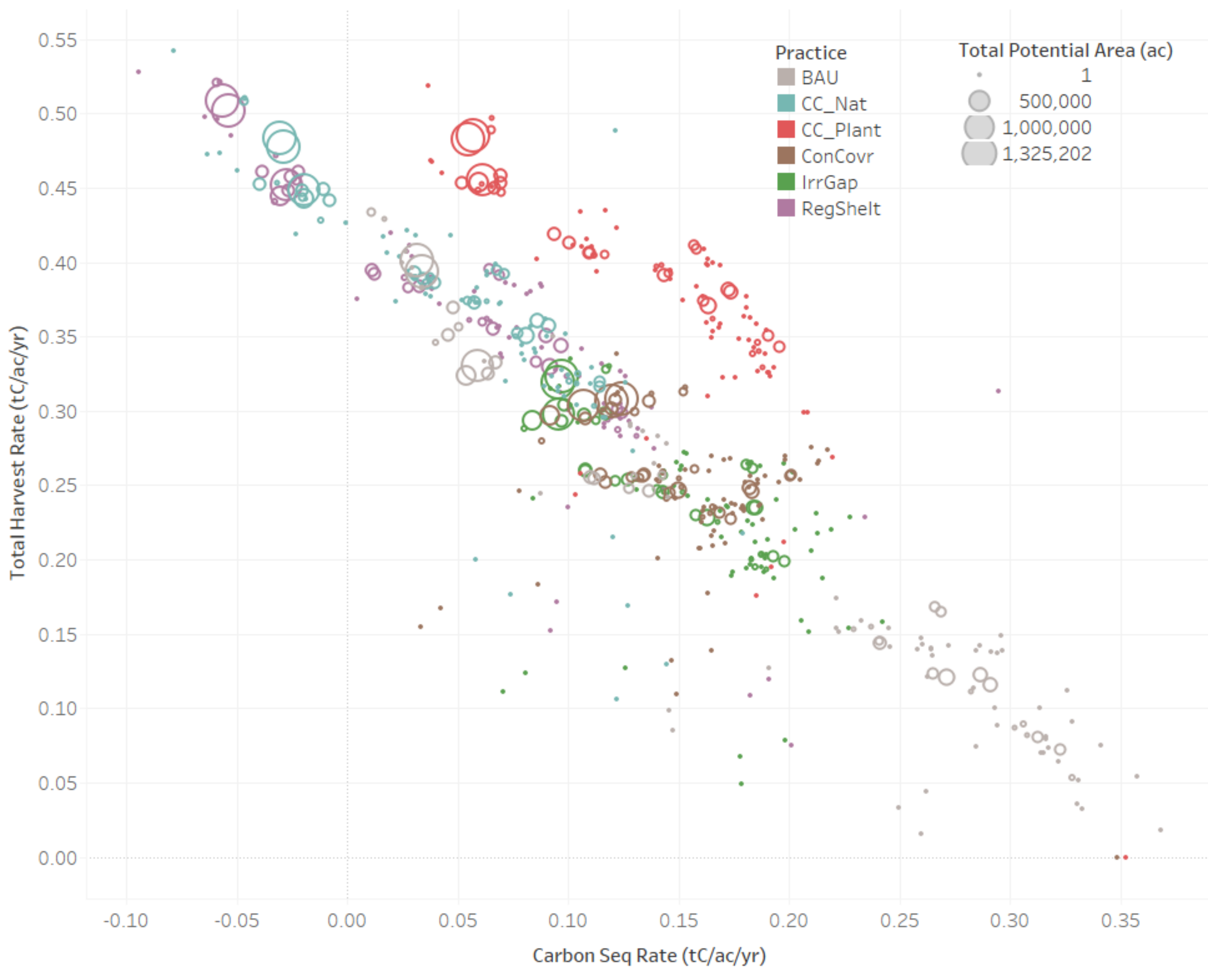

Figure 11. Carbon Sequestration versus Harvest Rate (Tons of Carbon per Acre per Year) by Silvicultural Treatment and Forest Type Combination

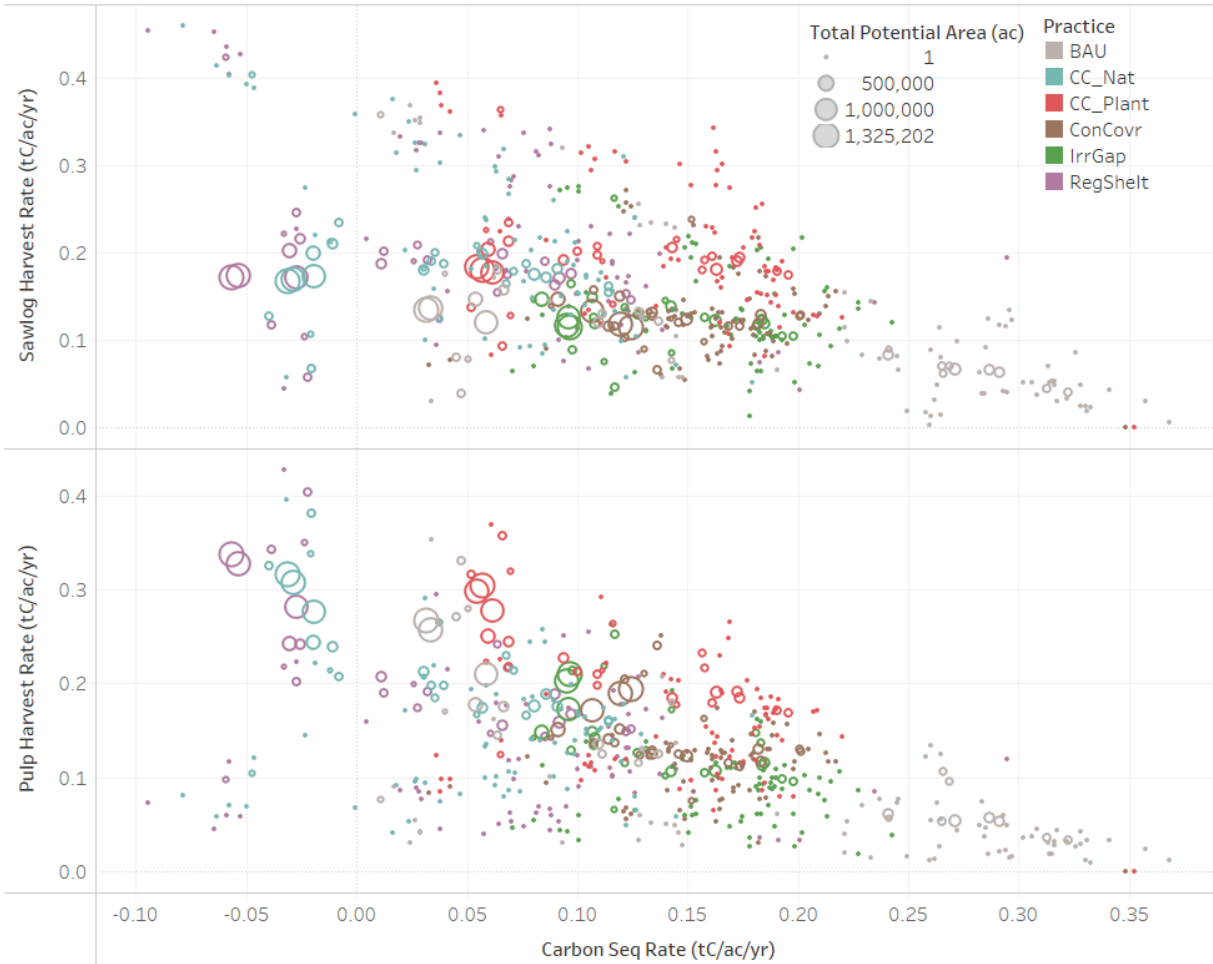

Figure 12. Carbon Sequestration versus Harvest Rate (Tons of Carbon per Acre per Year) by Silvicultural Treatment, Forest Type Combination, and Wood Product Type

Another metric of interest is the ratio of pulp and sawlogs relative to the total harvest. As noted, NM-LANDIS estimates this using an age-based metric (+/- 40 years old). On average, about 40 percent of the total harvest across the entire 7.5 million acres of forest in our study consists of sawlogs, although this amount can vary largely by forest type combination (Figure 13). Breaking this metric out by silvicultural treatment indicates that BAU has an average sawlog harvest of 40 percent, while continuous cover and irregular gap treatments have a mean sawlog harvest of 43 percent. The other three practices—which are all more intensive in terms of total removals per acre—have 41–42 percent of harvests as sawlogs. While the range is relatively small, we can still expect some treatments to need to harvest different amounts of area to meet specific harvest objectives.

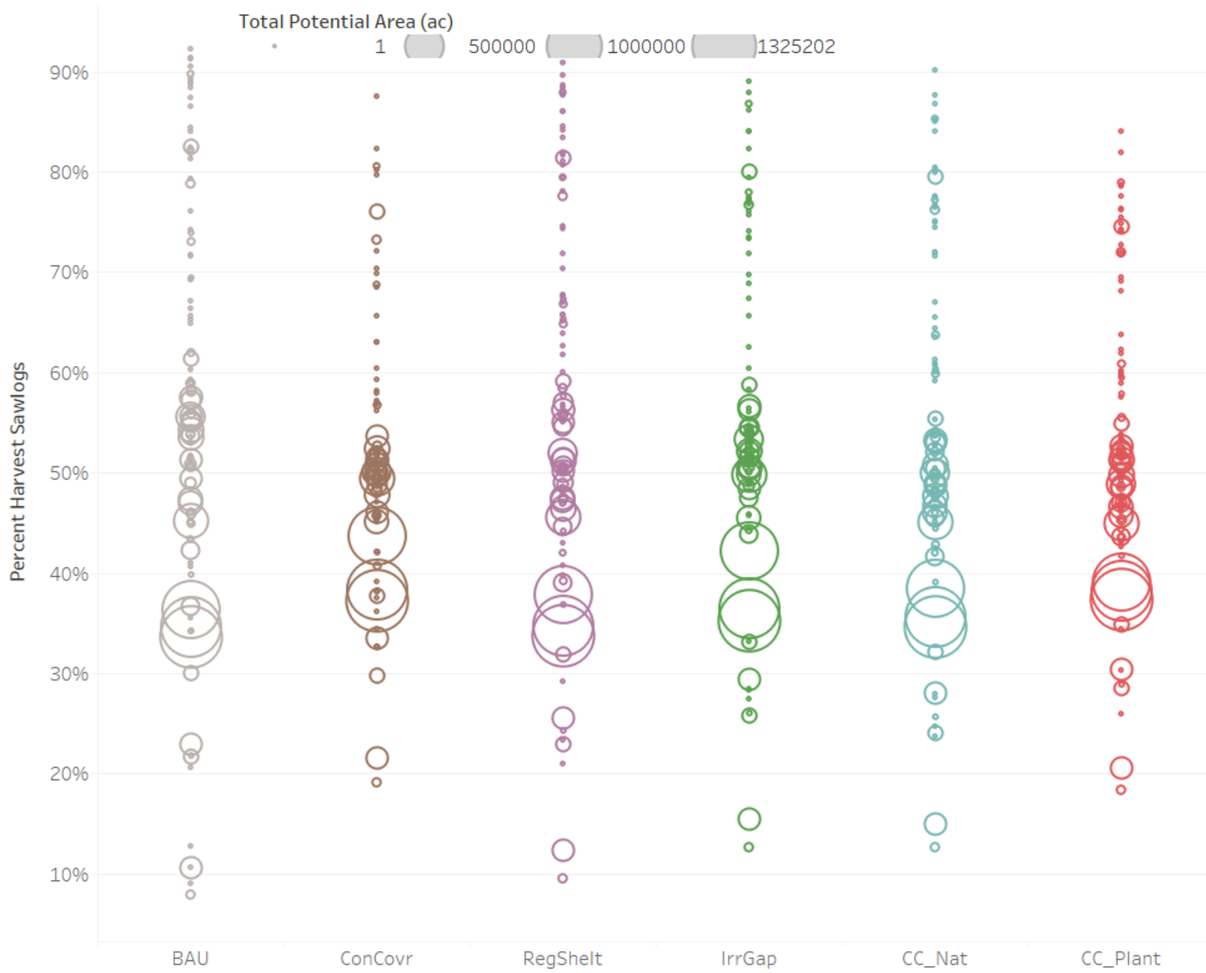

Figure 13. NM-LANDIS Estimated Average Percentage of Sawlog Harvest to Total Harvest by Silvicultural Treatment and Forest Type Combo Area Size

Economic Benefits and Costs

In consultation with the technical team and UMaine Forest Operations professor Anil Kizha, it was determined that the most appropriate approach for this study was to calculate net revenues (revenue less costs) to the landowner based on costs faced across multiple aspects of the supply chain, as that is likely to better capture the variation in returns for various treatments. As a result, net revenues (NR) for each silvicultural treatment were estimated as followed:

Net Revenue (NR) = Pulp Log Delivered Price x Pulp Harvest Quantity
+ Saw Log Delivered Price x Saw Harvest Quantity
– Hauling Cost – Logging Cost – Other Harvest Cost

where net revenues are estimated on a \$/acre basis, log prices are measured in \$/green tons, quantities are measured in green tons/acre, and costs are measured in \$/acre.

We estimated the logging costs of each forest type combination and silvicultural treatment using the following equation, which is based on Germain et al (2019):

Logging Cost = 59.29 – 1.2131 x Harvest_Volume

where logging costs are measured in $/acre and harvest volume is measured in green tons/acre.

Transport costs (i.e., hauling from loading site to mill) are assumed to be constant across all treatments and average $16.32/green ton.

Finally, we estimate the average break-even carbon price that landowners would need to receive to be indifferent between the BAU and alternative practice that sequesters more carbon in their forest (and harvested products):

$$\text{Break-even carbon price} = \frac{NRBAU - NRSCEN}{CarbonBAU - CarbonSCEN}$$

where the numerator is the difference in net revenue from the BAU and alternative future scenario (SCEN) and the denominator is the difference in carbon sequestration.

Using the NM-LANDIS harvest volume estimates and the methods described above, we can estimate the costs (Figure 14) and net revenues (Figure 15) for each silvicultural treatment by forest type combo. Results show that logging costs are highest for continuous cover and irregular gap, which are less-intensive operations, while the lowest cost is for the clearcut with natural generation. Accounting for the revenues earned from harvest indicates that clearcut with natural regeneration can potentially earn the highest amount of net revenue on average ($881/acre), with continuous cover earning the lowest ($378/acre). Again, the spread in the estimated returns can be attributed to the intensity of removals, for which lesser removals per acre results both in relatively lower revenue and higher costs. Further, although continuous cover and irregular gap treatments are expected to produce a greater proportion of sawlogs than the other treatments, our NM-LANDIS estimates indicate that the ratio of saw to pulp for those treatments are not high enough to compensate for the high logging and intermediate treatment costs required to achieve that ratio of output. Finally, our estimate that the BAU practice costs $37/green ton compares closely with the only other study we could find on total supply chain costs for the region, as Forest2Market (2015) estimated that northeast logging and transport costs averaged $37–$39/green ton.

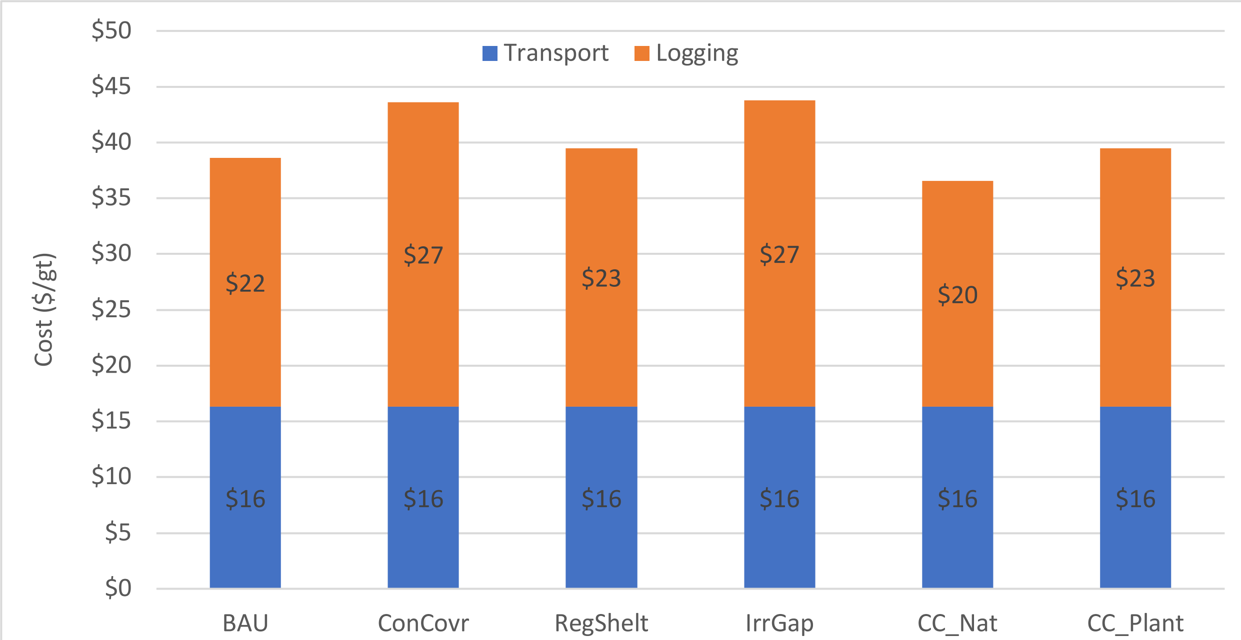

Figure 14. Estimated Average Total Costs by Silvicultural Treatment ($/Green Ton)

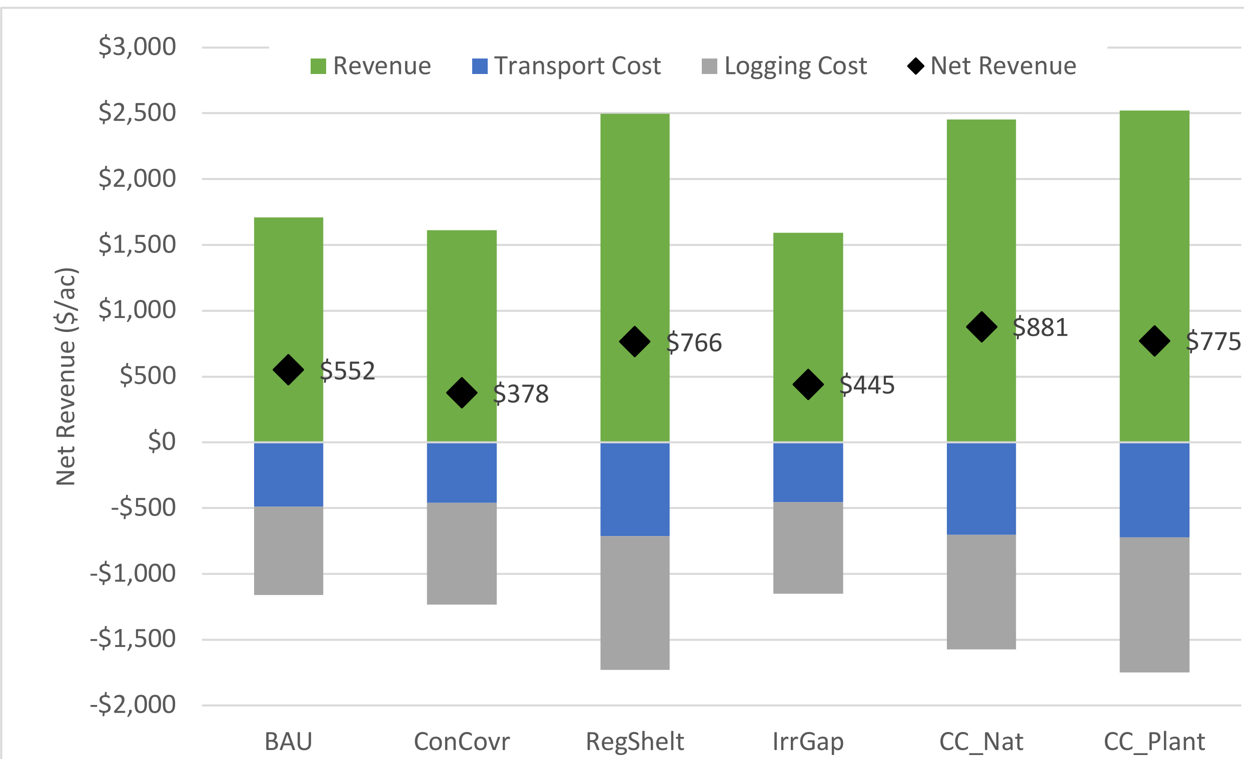

Figure 15. Estimated Average Net Revenue by Silvicultural Treatment ($/Acre)

MIFSM 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 is designed to link 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 socioeconomic futures, thereby allowing one to better understand the various trade-offs that could emerge as a result.
MIFSM's flexible optimization approach can be used, for example, to ask questions such as (1) What mix of alternative management practices would maximize carbon sequestration and storage on Maine's commercial timberlands? (2) How might the choice of silvicultural practices change if the goal were to maximize carbon without reducing annual harvests? and (3) 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 forest type combos that represent 7.5 million acres of Maine's commercial timberlands 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 NM-LANDIS, as well as logging price and harvest cost estimates gleaned from the literature (methods described above). In the general MIFSM model framework, NM-LANDIS represents the forest landscape model while the economic data represents the timber market model (Figure 16).

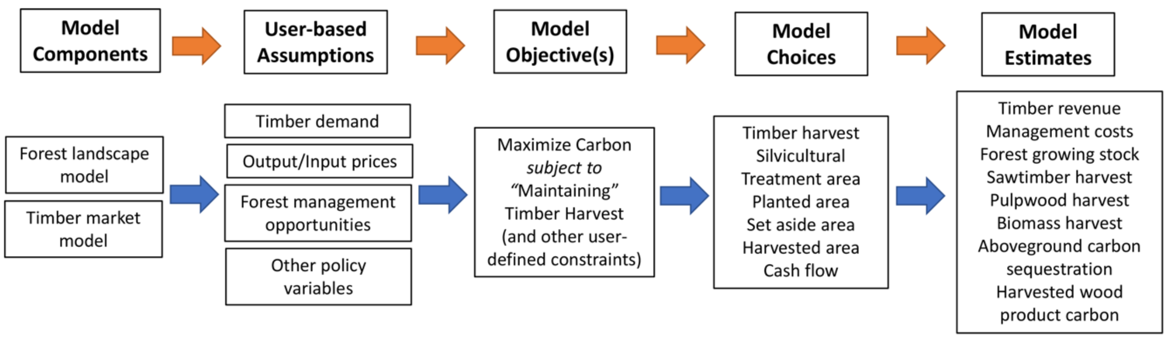

Figure 16. General MIFSM Model Framework

The Maine Integrated Forest Sector Model (MIFSM) is based on an agri-environmental economic model developed by Daigneault, Greenhalgh, and Samarasinghe (2018) to estimate the benefits and costs of implementing land-based practices at multiple scales. The spatially explicit model is based on a recursive-dynamic nonlinear mathematical programming model of Maine land use that is in this case spatially delineated at the forest combination level. Similar versions of the model have been used to assess GHG mitigation policy (Daigneault, Greenhalgh, and Samarasinghe 2018), climate change impacts (Monge et al. 2018), land restoration (Daigneault et al. 2017), erosion control (Fernandez and Daigneault 2017), and nutrient management (Daigneault et al. 2017).

The objective function estimates the amount of area (X) and level of forest production (i.e., timber commodities) that maximize total forest carbon sequestration ($CSeq$) or net revenue ($NetRev$) over time (t) from production across a given geographical area subject to feasible land use and land management (m) options for each forest type combination (f), accounting for timber production costs and output prices, and environmental factors such as stand quality, climate, and any "regulated" environmental outputs. The objective function is mathematically specified as:

$$Max\ Total\ CSeq = \sum_{f,m,t} \left(AGC_{f,m,t} + HWPC_{f,m,t}\right) * X_{f,m,t}$$

$$\text{or } Max\ Net\ Revenue = \textstyle\sum_{f,m,t} \left(P_a A_{f,m,t} - C_{f,m,t}\right) * X_{f,m,t}$$

where the decision variable X is the area allocated to each silvicultural activity.
AGC is aboveground carbon sequestration, HWPC is harvested wood product carbon sequestration, P is the product output price, A is the annual timber output quantity of product a (sawlogs or pulpwood), and C is the cost of the silvicultural treatment implemented to yield that timber.

Summing the carbon, revenue, and costs of production across the total forested region (*r*), which consists of several forest types (*f*), and forest management options (m), yields the total net revenue for the geographical area of concern. The carbon and net revenue maximization problems are not limited to the output prices and costs of production but also by a number of production, land, technology, and environmental constraints. The model solves the maximization problem for the entire duration of the study time period (2010–2070), subject to resource, technological, and policy constraints.

Production is constrained by the product-balance equation using a processing coefficient (α^{proc}) that specifies what timber commodities can be produced by a given silvicultural activity and forest type combo in the study area, where summing across all outputs helps to meet the harvest target constraint (i.e., 2 MtC/y). Additional constraints break out the total harvest specifically into annual pulp and sawlog harvest targets (approx. 60/40 of total).

The model also assumes a fixed land area constraint such that total land area must remain constant for each forest combo type. We also include a non-negativity constraint such that the area allocated to each silvicultural treatment must be greater than or equal to zero.

Additional constraints are also considered for the extent of silvicultural practices that can be employed by each silvicultural treatment, which can vary by scenario. These constraints include the amount of land that can be allocated to permanent set-aside, clearcut, or implemented as one of the other five silvicultural practices as described in the Forest Type Aggregation section.

The MIFSM model is programmed in GAMS and solved using the MINOS solver. The 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. 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 revenue values of each possible combination. As described above, we use annualized mean averages from NM-LANDIS to parameterize MIFSM, and therefore the model produces estimates for average annual carbon and total net revenue over the entire 60-year model period.

Alternative Future Scenario Analysis

To test model functionality and potential impacts of individual practices, we first conducted a number of model runs that maximized carbon sequestration across the forest landscape subject to meeting a 2 MtC/y harvest target, but only allowing a single silvicultural practice to be employed to meet that target, and having the remaining land be allocated to the no-harvest set-aside.

Next, the technical team jointly developed a set of alternative futures to analyze. These futures varied objectives, eligible practices, harvest targets, timber product prices, management costs, and allocation of timber removals to HWPs. A summary of the key assumptions for the three main alternative futures, as well as a no-harvest "let it grow" scenario, are listed in Table 5.

Table 5. FCCL Alternative Future Scenario Parameterization and Assumptions

#	Future	Scenario	Objective	Eligible Practices	Total Forest Area (ac)	Max Set Aside Area (acres)	Max Total Clearcut Area (acres)	Max Clearcut + Plant Area (acres)	Total Harvest (tC/y)	Pulp + Biomass Harvest (tC/y)	Saw Harvest (tC/y)	Sawlog Prices ($/gt)	Pulp/Biomass Prices ($/gt)	Management Costs ($/ac)	HWP C Storage
1-1	Current Trends	BAU - Max Net Revenue	Max NetRev	BAU Mix	7,583,441	1,390,296	973,392	247,030	2,000,000	1,200,000	800,000	Historical Mean	Historical Mean	Mean -0.25%/yr	Historical Mean
1-2	Current Trends	Current CC / Set Aside	Max C	All w/sideboards	7,583,441	1,390,296	619,314	619,314	2,000,000	1,200,000	800,000	Historical Mean	Historical Mean	Mean -0.25%/yr	Historical Mean
1-3	Current Trends	Mod CC / Set Aside	Max C	All w/sideboards	7,583,441	1,737,870	1,238,629	1,238,629	2,000,000	1,200,000	800,000	Historical Mean	Historical Mean	Mean -0.25%/yr	Historical Mean
1-4	Current Trends	Max CC / Set Aside	Max C	All w/sideboards	7,583,441	7,583,441	7,583,441	7,583,441	2,000,000	1,200,000	800,000	Historical Mean	Historical Mean	Mean -0.25%/yr	Historical Mean
2-1	Tech Innovation	BAU - Max Net Revenue	Max NetRev	BAU Mix	7,583,441	0	973,392	247,030	2,259,557	1,380,580	878,977	Mean +0.75%/yr	Mean +0.75%/yr	Mean -0.5%/yr	50% Pulp to Long-last product
2-2	Tech Innovation	Current CC / Set Aside	Max C	All w/sideboards	7,583,441	1,390,296	619,314	619,314	2,200,000	1,300,000	900,000	Mean +0.75%/yr	Mean +0.75%/yr	Mean -0.5%/yr	50% Pulp to Long-last product
2-3	Tech Innovation	Mod CC / Set Aside	Max C	All w/sideboards	7,583,441	1,737,870	1,238,629	1,238,629	2,200,000	1,300,000	900,000	Mean +0.75%/yr	Mean +0.75%/yr	Mean -0.5%/yr	50% Pulp to Long-last product
2-4	Tech Innovation	Max CC / Set Aside	Max C	All w/sideboards	7,583,441	7,583,441	7,583,441	7,583,441	2,200,000	1,300,000	900,000	Mean +0.75%/yr	Mean +0.75%/yr	Mean -0.5%/yr	50% Pulp to Long-last product
3-1	Low Innovation	BAU - Max Net Revenue	Max NetRev	BAU Mix	7,583,441	1,390,296	973,392	247,030	1,950,000	1,150,000	800,000	Historical Mean	Mean -0.5%/yr	Historical Mean	Historical Mean
3-2	Low Innovation	Current CC / Set Aside	Max C	All w/sideboards	7,583,441	1,390,296	619,314	619,314	1,950,000	1,150,000	800,000	Historical Mean	Mean -0.5%/yr	Historical Mean	Historical Mean
3-3	Low Innovation	Mod CC / Set Aside	Max C	All w/sideboards	7,583,441	1,737,870	1,238,629	1,238,629	1,950,000	1,150,000	800,000	Historical Mean	Mean -0.5%/yr	Historical Mean	Historical Mean
3-4	Low Innovation	Max CC / Set Aside	Max C	All w/sideboards	7,583,441	7,583,441	7,583,441	7,583,441	1,950,000	1,150,000	800,000	Historical Mean	Mean -0.5%/yr	Historical Mean	Historical Mean
4-1	Let it Grow	All Set Asides	Max C	Set Asides Only	7,583,441	7,583,441	0	0	0	0	0	N/A	N/A	N/A	N/A

MIFSM Results

Individual Treatment Scenarios

Key estimates for the individual treatment scenarios are listed in Table 6. The results highlight that each practice is likely to produce net carbon sequestration across the study area, but at different levels, with no-harvest, clearcut-and-plant, and continuous cover practices generating the highest amounts on average. However, the proportion of land harvested versus land allocated to a no-harvest set-aside varies significantly across treatment scenarios (Figure 17). That is, more intensive treatments result in lower carbon sequestration rates on the forestland where those practices are implemented, but their ability to supply more timber on a per-acre basis means that there is more land that can be allocated to set-asides, which have the highest sequestration rates (Table 7). Further, we find that the low-intensity harvest level associated with continuous cover and irregular gap means that there would have to be more area allocated to those treatments relative to the other options in order to achieve the 2 MtC/y harvest target (approx. 90 percent of all forested area), thereby resulting in more harvesting in areas currently considered less accessible, such as riparian areas.

Our analysis of individual treatments also indicates that each practice will produce different ratios of pulp and sawlogs to meet the 2 MtC annual harvest constraint, with continuous cover and irregular gap likely to produce a higher proportion of sawlogs. However, the high cost of implementing these practices means that their annual net revenue is much lower than most of the other practices under consideration.

Table 6. Key Estimates for Individual Treatment Scenarios

Estimate	Partial	Cont Cover	Reg Shelt	Irr Gap	CC Nat Reg	CC & Plant	No Harvest
C Sequestration (tCO2e/y)	3,778,407	4,162,630	3,662,129	3,839,998	3,780,490	5,148,257	8,726,741
Forest Area (acres)	7,583,101	7,583,101	7,583,101	7,583,101	7,583,101	7,583,101	7,583,101
Harvested Forest Area (acres)	5,691,584	6,889,594	4,253,747	6,801,639	4,364,179	4,366,120	0
Annual Net Revenue (mil $/y)	$71.4	$45.8	$72.4	$46.1	$80.2	$65.5	$0
Annual Harvest (tC/y)	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	0
Annual Saw Harvest (tC/y)	730,041	856,673	724,550	834,726	768,617	795,854	0
Annual Pulp Harvest (tC/y)	1,269,959	1,143,327	1,275,450	1,165,274	1,231,383	1,204,146	0

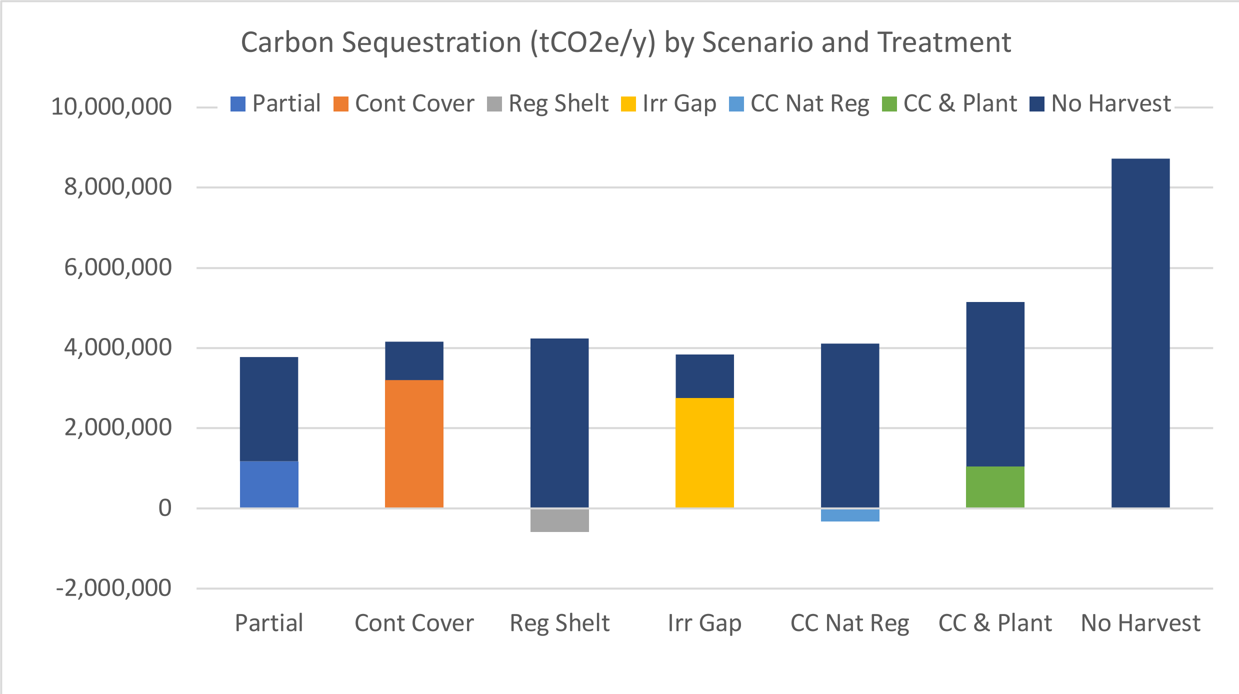

Figure 17. Total Carbon Sequestration by Treatment and Individual Treatment Scenario

Table 7. Mean Carbon Sequestration Rates by Treatment (tCO2e per Acre per Year) for Individual Scenarios

Individual Treatment Scenario	Specific Treatment Rate*	Total Study Area Rate^
Partial	0.21	0.50
ConCovr	0.47	0.55
RegShelt	-0.14	0.48
IrrGap	0.41	0.51
CC_Nat	-0.08	0.50
CC_Plant	0.24	0.68
No Harvest	1.15	1.15

*The specific treatment rate refers to sequestration rate across the area harvested using the individual treatment (practice) of interest in each scenario.
^The total study area rate accounts for the average sequestration rate across the entire 7.6-million-acre study area (i.e., individual treatment + no-harvest area).

Alternative Future Scenarios

Table 8. Alternative Future 1: Current Trends

Estimate	Current Trends-BAU - Max NetRev	Current Trends-Current CC / Set Aside	Current Trends-Mod CC / Set Aside	Current Trends-Max CC / Set Aside
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	$85,964,970
Annual Harvest (tC/y)	2,000,000	2,000,000	2,000,000	2,000,000
Annual Saw Harvest (tC/y)	800,000	800,000	800,000	800,000
Annual Pulp Harvest (tC/y)	1,200,000	1,200,000	1,200,000	1,200,000
Change From Base				
C Sequestration (tCO2e/y)	-	736,979	941,758	1,497,168
Annual Harvest (tC/y)	-	0	0	0
Annual Saw Harvest (tC/y)	-	0	0	0
Annual Pulp Harvest (tC/y)	-	0	0	0
Annual Net Revenue ($/y)	-	-$11,627,197	-$9,614,681	$8,498,831
Break Even $/tCO2e (from Scenario BAU)	**-**	**$15.78**	**$10.21**	**-$5.68**
% Change Carbon Sequestration:	**-**	**20.4%**	**26.1%**	**41.4%**

Table 9. Alternative Future 2: Tech Innovation

Estimate	Tech Innov-BAU - Max NetRev	Tech Innov-Current CC / Set Aside	Tech Innov-Mod CC / Set Aside	Tech Innov-Max CC / Set Aside
C Sequestration (tCO2e/y)	3,749,125	4,482,764	4,685,683	5,426,595
Forest Area	7,583,265	7,583,441	7,583,441	7,583,441
Annual Net Revenue ($/y)	$141,842,858	$133,985,855	$131,711,009	$147,854,358
Annual Harvest (tC/y)	2,259,000	2,200,000	2,200,000	2,200,000
Annual Saw Harvest (tC/y)	879,000	900,000	900,000	900,000
Annual Pulp Harvest (tC/y)	1,380,000	1,300,000	1,300,000	1,300,000
Change From Base				
C Sequestration (tCO2e/y)	-	733,639	936,558	1,677,470
Annual Harvest (tC/y)	-	-59,000	-59,000	-59,000
Annual Saw Harvest (tC/y)	-	21,000	21,000	21,000
Annual Pulp Harvest (tC/y)	-	-80,000	-80,000	-80,000
Annual Net Revenue ($/y)	-	-7,857,004	-10,131,849	6,011,500
Break Even $/tCO2e (from Scenario BAU)	**-**	**$10.71**	**$10.82**	**-$3.58**
% Change Carbon Sequestration:	**-**	**19.6%**	**25.0%**	**44.7%**

Table 10. Alternative Future 3: Low Innovation

Estimate	Low Innov-BAU - Max NetRev	Low Innov-Current CC / Set Aside	Low Innov-Mod CC / Set Aside	Low Innov-Max CC / Set Aside
C Sequestration (tCO2e/y)	3,755,342	4,540,539	4,735,338	5,183,555
Forest Area	7,583,265	7,583,441	7,583,441	7,583,441
Annual Net Revenue ($/y)	$38,962,656	$33,078,363	$35,727,298	$53,424,162
Annual Harvest (tC/y)	1,950,000	1,950,000	1,950,000	1,950,000
Annual Saw Harvest (tC/y)	800,000	800,000	800,000	800,000
Annual Pulp Harvest (tC/y)	1,150,000	1,150,000	1,150,000	1,150,000
Change From Base				

C Sequestration (tCO2e/y)	-	785,197	979,997	1,428,214
Annual Harvest (tC/y)	-	0	0	0
Annual Saw Harvest (tC/y)	-	0	0	0
Annual Pulp Harvest (tC/y)	-	0	0	0
Annual Net Revenue ($/y)	-	-5,884,293	-3,235,358	14,461,506
Break Even $/tCO2e (from Scenario BAU)	-	$7.49	$3.30	-$10.13
% Change Carbon Sequestration:	-	20.9%	26.1%	38.0%

Table 11. Alternative Future: Let It Grow

Estimate	Current Trends-BAU - Max NetRev	Let It Grow
C Sequestration (tCO2e/y)	3,613,497	8,726,741
Forest Area	7,583,441	7,583,006
Annual Net Revenue ($/y)	$77,466,139	0
Annual Harvest (tC/y)	800,000	0
Annual Saw Harvest (tC/y)	1,200,000	0
Annual Pulp Harvest (tC/y)	3,613,497	0
		Change From Base
C Sequestration (tCO2e/y)		5,113,245
Annual Harvest (tC/y)		-2,000,000
Annual Saw Harvest (tC/y)		-800,000
Annual Pulp Harvest (tC/y)		-1,200,000
Annual Net Revenue ($/y)		-$77,466,139
Break Even $/tCO2e (from Scenario BAU)		**$15.15**
% Change Carbon Sequestration:		**141.5%**

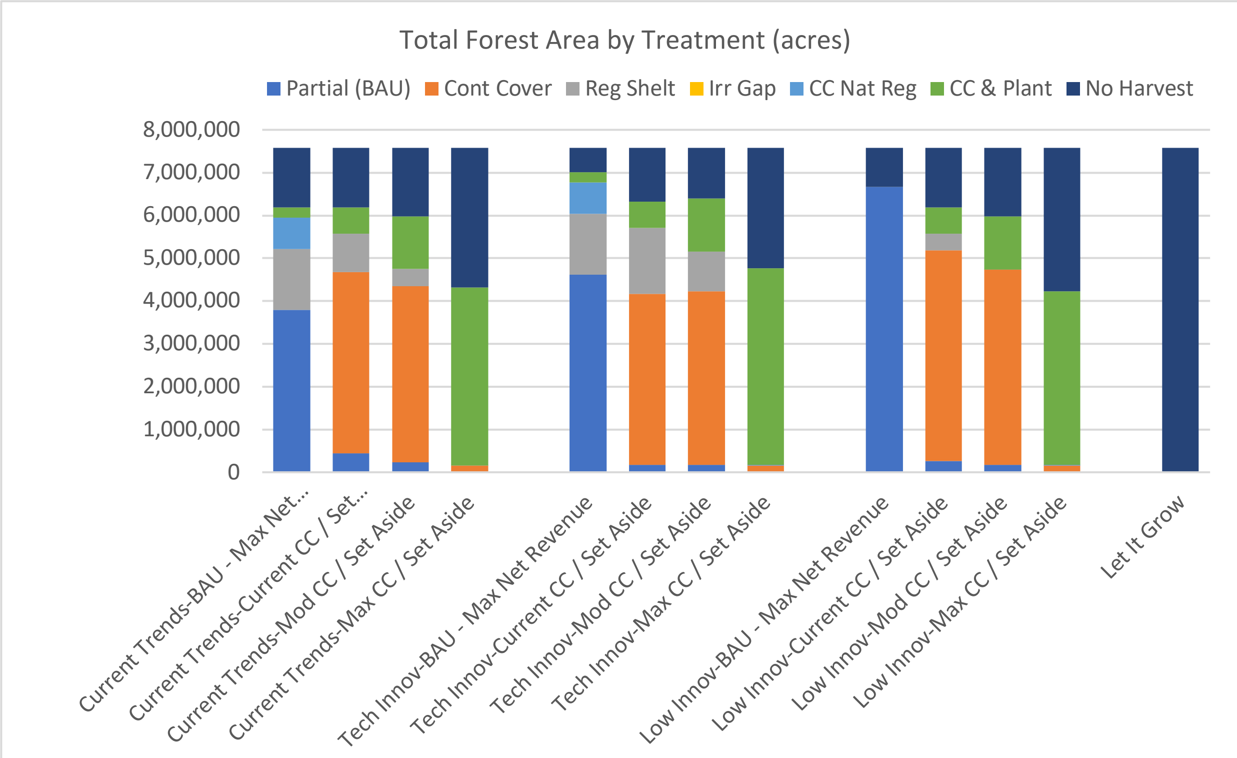

Figure 18. Area by Silvicultural Treatment and Alternative Future Scenario

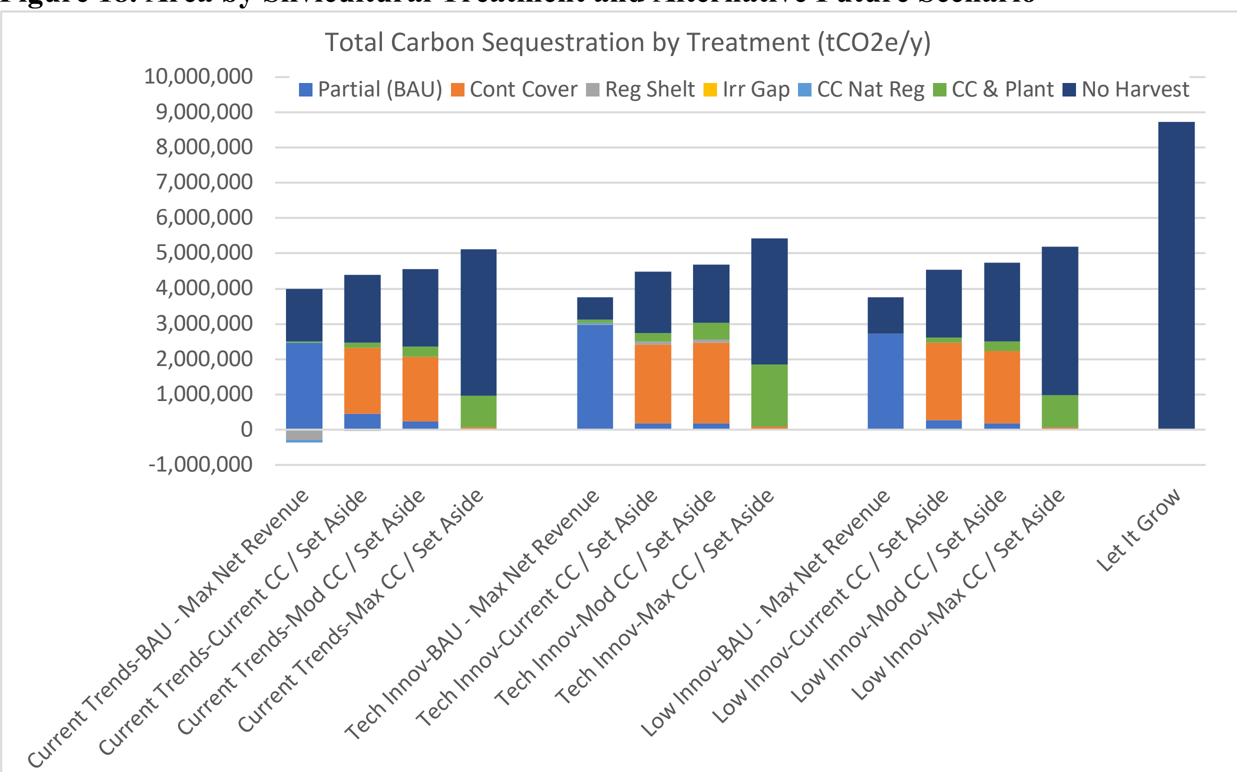

Figure 19. Total Carbon Sequestration by Silvicultural Treatment and Alternative Future Scenario

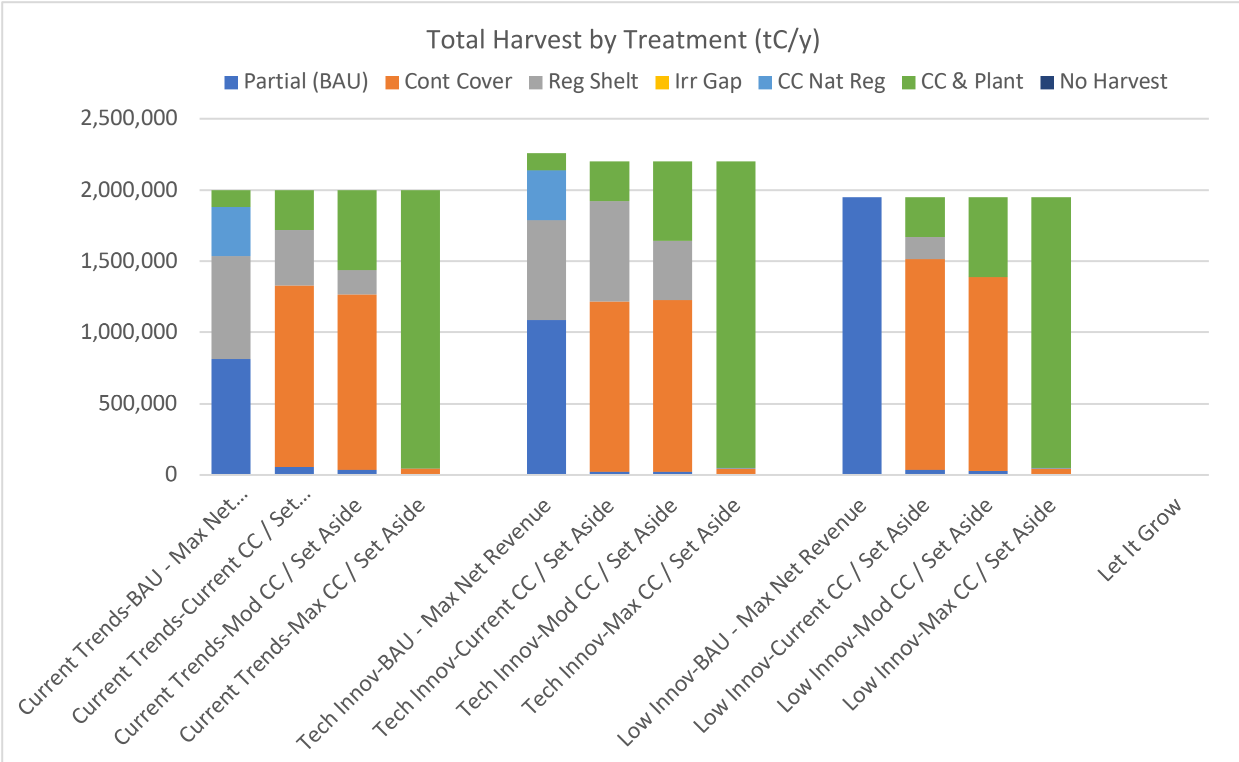

Figure 20. Total Harvest by Silvicultural Treatment and Alternative Future Scenario

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Appendix D:
An Introduction to the Province of Nova Scotia's Silviculture Program

A Presentation to the Forest Carbon for Commercial Landowners Group |
Ian Johnstone, Wagner Forest NS, Ltd.

Background of Intensive Silviculture Programs in Nova Scotia

- 1980’s to 1995= Federal Provincial Funding agreements with a focus of management of Private Land in many Canadian provinces.
- Five year funding agreements between Provincial and Federal government for forest management activities 70% funding from Federal Government, 20% Provincial and 10% from the landowner.
- Administered by the Province :
  - Provided funding for administration of landowner co-ops, joint venture (management plans etc).
  - Silviculture focused on precommercial thinning, planting and herbicide.
- Program was cancelled in 1996 due to budgetary constraints with the Federal Government.

2

Provincial Concerns over Sustainability

- Increased expansion of sawmill industry in 1990's
- Government and industry were concerned that harvest levels were sustainable over time.
- There were significant exports into New Brunswick at the time, but no system to track them
- NS Forests 10,000,000 acres
- Softwood harvest levels were estimated at 5.5 to 6,000,000 tonnes
- Late 1990's – 25% large Private, 25% crown, 50% small private
  - Small Private = less than 5,000 acres
- How do we get private landowners to grow more wood and continue to participate in the marketplace.

3

Registry of Buyers

- Intent was to grow more fiber over a shorter period of time.
- Incentivize the mills to complete an efficient program and landowners to participate in the marketplace.
- Department of Natural Resources (DNR) employees' ensure mills are meeting obligations.
- Administered by Industry, funded by a combination of industry and the Provincial government.

4

Forest Sustainability Regulations

- Started in 1998,updated in 2000
- Requires Industrial Wood Processing facilities in the Province that use more than 5,000 tonnes become a registered buyer and they must complete a silviculture program on NS Private land in proportion to the amount of fiber they purchase.
- Mills have an obligation of $3.00 for each tonne of softwood and $.58 for each tonne of hardwood purchased.
- Two Options to Meet Liability:
  - Completing a silviculture program on Private land based on the amount of their liability. (self administered 'pay themselves' 10% of liability for administration costs.)
  - Cash contribution to the Forest Sustainability Fund.

5

Mechanics of the Registered Buyers System

- Each RB must submit a Wood Acquisition Plan by March (2020) of each year for calendar year purchases.
- Each RB must conduct a silviculture program or contribute to the Sustainable Forestry Fund based on planned purchases during that year.
- The following year (2021) each buyer must report actual purchases /consumption.
- GIS shapefiles are submitted in February (2021) to DNR as evidence of the silviculture work was completed.
- DNR audits 10% of submissions within 18 months following submissions.
- RB’s that complete their own program are credited 10% of the value of the program as an administration expense.
- Maximum 25% of Programs from landowners with more than 5,000 acres of holdings.
- Mills are reimbursed the government incentive portion at the end of the calendar year.

6

2020 Silviculture Credit Limits for Wood Acquisition Plans

- Credits: 1 credit= $1.00
- Planting: 240 credits/acre
- Precommercial Thinning: 320 credits/acre
- Natural regeneration: 28 credits/acre
- Commercially Thinning: 220 credits/acre

7

Provincial Funding Component

- Provincial government will provide credits for certain treatments. Higher credits to incentivize treatments they feel are more important.
  - Commercial thinning 75%
  - Selection harvesting 75%
  - Pre-commercial thinning 50%
  - Planting 33%
  - Herbicide 0%
  - Natural Regeneration 0%

- Treatments are only provided to small landowners. Large Private and Industrial lands (owned by mills), receive no incentive.

8

Example

- Sawmill 'A' purchases 500,000 tonnes of softwood studwood/logs.
- There is a $1,500,000 silviculture liability that must be completed.
- Sawmill "A" sells 250,000 tonnes of residual chips to pulpmill 'B', transferring 50% of the liability to the pulpmill.
- Sawmill administers their own program and must complete $675,000 of silviculture work. ($750,000- $75,000 (administration).
- If work is completed by CT = $675,000 x 75% credited = $168,750 net cost to mill
  - 3,068 acres would need to be thinned, mill is reimbursed $506,250 by DNR
- Example with a variety of treatments completed:

	Acres	Credit Value/Treatment	Total Credits	Incentive	Reimbursed by Government	Net Cost
PCT	800	320	$256,000.00	50%	$ 128,000.00	$128,000.00
Planting	830	240	$199,200.00	33%	$ 65,736.00	$133,464.00
CT	1000	220	$220,000.00	75%	$ 165,000.00	$ 55,000.00
			$675,200.00		$ 358,736.00	$316,464.00

9

Results

- Market based, business to business arrangement.
- Limited government involvement.
- Most all RB’s administer their own program, use it as a tool to develop relationships with private landowners.
- At the peak of softwood harvest levels in 2005, there was $12,000,000 of silviculture work completed on an annual basis. Today, $5,000,000.

10