Final Report

Maine Forestry and Agriculture Natural Climate Solutions Mitigation Potential

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Table of Contents

Executive Summary

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions 80% by 2050 and to have Maine's net GHG emissions (gross emissions less carbon sequestration from forestry, agriculture, and marine sinks) be equal to zero, or 'net zero', by 2045. To achieve its climate change mitigation goals, Maine may need to remove additional carbon from the atmosphere (i.e., negative emissions) and sequester it in soils, sediments, biomass, and forest products. Natural climate solutions (NCS) such as improved cropland nutrient management, planting trees, and conservation that sequester carbon or limit GHG emissions can affect both near-term GHG mitigation goals and enhance ecosystem services. However, a comprehensive assessment of potential NCS practices and their cost/benefits across Maine's primary sectors has yet to be attempted.

This report presents findings from a part of the larger 'Maine Natural Climate Solutions Initiative' project that seeks to: (1) assess current practices to determine the degree to which foresters and farmers are using NCS; (2) determine the most cost-effective NCS for Maine; (3) understand key barriers to adopting NCS; and (4) generate information about which practices can be implemented on a broader scale. The findings presented here were developed using the following methodology. First, we modeled a 'baseline' or 'business as usual' (BAU) pathway against which all other scenarios or pathways were compared. Next, we used a mix of expert input, available data, and modeling to develop a broad suite of potential NCS practices that could feasibly be implemented in Maine. Third, we derived estimates of the cost and effectiveness of implementing the NCS practices under consideration. Last, we conducted both alternative future scenario and sensitivity analyses to assess how the estimated impacts on carbon and costs could vary under different model assumptions and pathways.

In recent years, Maine's forests have been sequestering nearly 70% of the state's reported annual gross anthropogenic greenhouse gas emissions and are predicted to continue to do so under a range of alternative management scenarios and potential futures. Using a forest landscape model and data available for 9.1 million acres of forest in northern Maine, we determined that most forest management NCS practices can be implemented at a cost of $10-20 per ton carbon dioxide equivalent (tCO_2e)[1], which is relatively inexpensive compared to most non-NCS opportunities (Figure 1). Our modeled scenario for jointly implementing a mix of forest NCS practices across northern Maine could yield approximately 5.3 million tCO_2e/yr in additional carbon sequestration at a total cost of $79 million/yr or $15/$tCO_2e$. This approach was found to be more effective than single-practice scenarios such as extending stand rotation lengths or increasing the proportion of the annual harvest that was clearcut and naturally regenerated. Nearly all scenarios tested had less than a 10% reduction in annual harvest levels, thereby resulting in limited potential leakage (i.e., displacement of emissions). Further, we found that implementing NCS had important effects on other ecosystem services such as habitat, highlighting the need to think beyond carbon and timber when considering different management options.

For Maine agriculture, farmers could amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and use anaerobic digesters to manage dairy manure waste, thereby collectively

[1] Forest carbon estimates in this study are reported in either tons carbon dioxide equivalent (tCO_2e) or tons carbon (tC). 1 tC = 3.67 tCO_2e, while 1 tCO_2e = 0.27 tC.

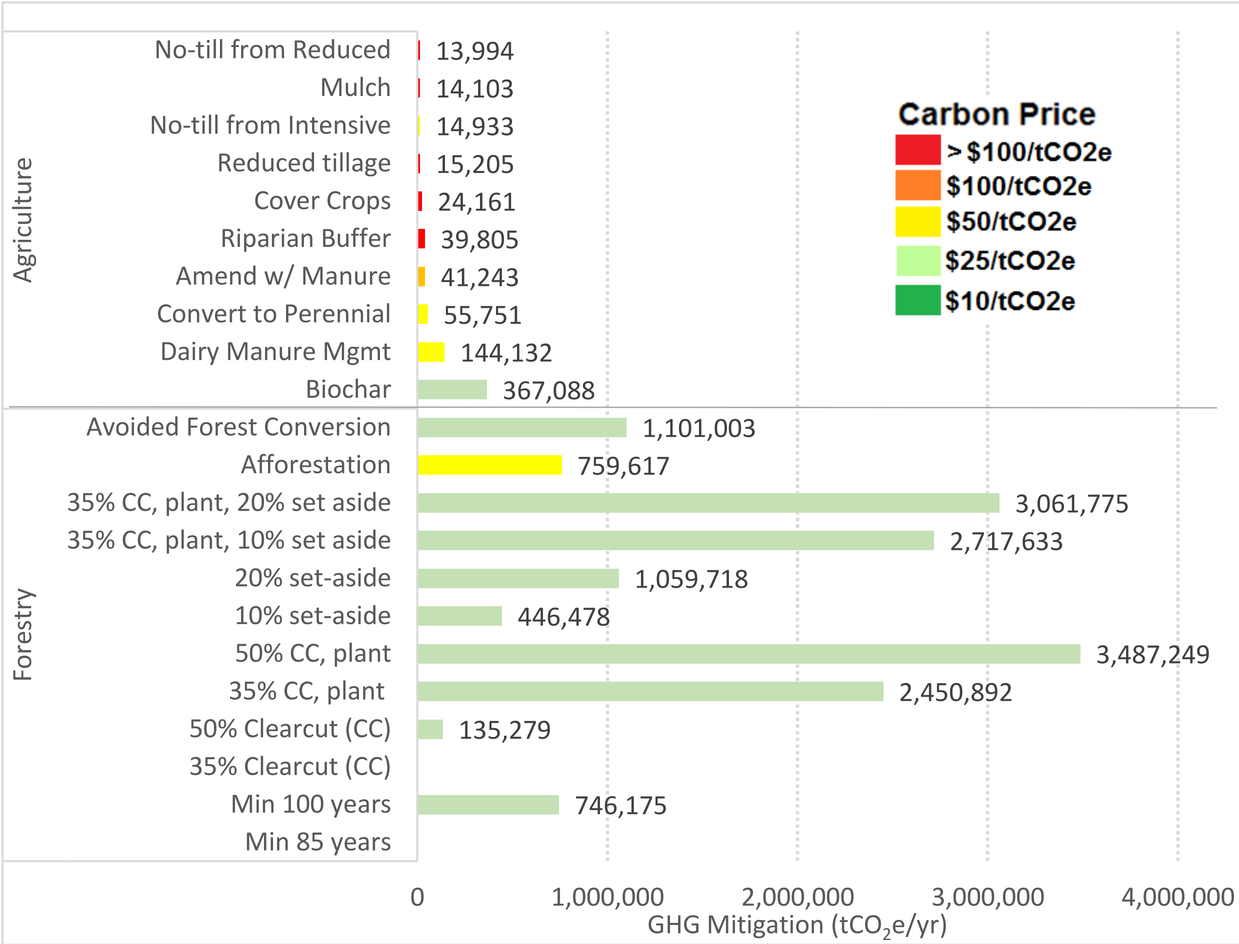

Figure 1. Summary of Maine NCS mitigation potential (tCO_2e/yr) and break-even carbon price ($\$/tCO_2e$).

mitigating up to 566,000 tCO_2e/yr in GHG emissions or nearly 1.5 times the sector's current annual emissions (Figure 1). This combined approach for the agricultural sector is estimated to cost $18.9 million/yr or $33/$tCO_2e$. Consequently, uncertainties notwithstanding, this analysis showed that Maine's agricultural sector has the potential to be carbon neutral or even net negative.

This project also conducted one-on-one interviews and focus groups to explore the potential technical, financial, social, and/or policy barriers that stakeholders face in implementing the NCS practices, as well as identifying potential opportunities. These findings informed the assumptions we used in the scenario analysis. Participants from both the forestry and agricultural sectors identified cost, lack of labor, and administrative burden as critical barriers to wider adoption of the NCS practices modeled in this study. Both groups stated that financial incentives, particularly assistance with up-front costs, would encourage broader implementation of NCS practices. Small forest landowners and farmers also identified technical support for implementing practices or pursuing financial assistance as an important opportunity to enable adoption.

The quantitative analysis included detailed sensitivity and scenario analyses to assess how NCS mitigation levels and costs could range under varying assumptions. This included developing and modelling five shared socioeconomic pathways (SSPs) following the Intergovernmental Panel on Climate Change's (IPCC) scenario framework to explore possible futures for the land use sector in Maine. We found that the scenarios that assumed strong institutional support and technical innovation for adopting NCS practices have the potential to achieve uptake and mitigation in line with the estimates presented in Figure 1. The SSP-based analysis indicated that focusing largely on implementing cost-effective NCS practices could eliminate Maine's land sector emissions over the next 25 years and help achieve the state's broader carbon neutrality goals at a cost of $21-33 mil/yr for forestry and $25-29 mil/yr for agriculture. In contrast, the more pessimistic pathways under which there is less technological innovation and a lack of emphasis on implementing NCS practices would achieve lower overall mitigation, thus reducing Maine's ability to achieve its 2045 net-zero goal.

As with most research, this analysis has important limitations that can and should be refined in future efforts as more data become available. Nonetheless, this work represents a critical step during implementation of Maine's climate action plan, providing a basis for science-informed decision-making by exploring the potential benefits of alternative NCS practices.

1. Introduction

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions 80% by 2050 and to have their net GHGs (gross emissions less carbon sequestration from forestry, agriculture, and marine sources) be equal to zero, or 'net zero', by 2045 (Greenhouse Gas Emissions Reductions, 2019). The Maine Department of Environmental Protection (DEP) tracks gross GHG emissions from numerous sources including the energy and agricultural sectors; however, they do not account for carbon (C) sequestration from the state's land use sectors (*Eighth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals*, 2020). Maine's natural and working lands are likely to provide a significant contribution towards achieving the state's climate change mitigation goals, but more research is needed to better understand the cost and effectiveness of implementing various practices across the landscape.

Maine's GHG reduction goals reflect the evidence of current and potential future harmful impacts climate change could have on the state's people, ecosystems, and economy. Milder winters and earlier springs adversely impact forestry and farming in Maine (Dupigny-Giroux et al., 2018). The Northeast is warming faster than the rest of the U.S. (Karmalkar & Bradley, 2017), and Maine's temperature has increased by 3.2 degrees Fahrenheit since 1895, with greater increases along the coast. In Maine, we are acutely aware of the changing conditions in the Gulf of Maine, particularly in marine fisheries, and in coastal communities. However, Maine's terrestrial environment is also strongly influenced by changing climatic conditions that are likely to place increasing stress on Maine's forests, particularly those species that either are at their northern or southern limit or are vulnerable to emergent pests and pathogens. The growing season in Maine is two weeks longer than it was in 1950, and the state is experiencing an increase in total precipitation and precipitation intensity, with more likely to come (Fernandez et al., 2020). This increased precipitation can cause delays in planting, soil compaction, soil erosion, and agricultural runoff. The frequency of heavy rainfall events before the final frost has been increasing and could prevent farmers from taking advantage of earlier springs and reduce the number of days that fields can be worked because they are overly wet (Wolfe et al., 2018). Scientists also expect warmer winters to increase the pressure from pests and weeds often restricted by winter temperature minimums, which are warming faster than those of all other seasons. Rural communities have limited economic resilience because of a lack of redundancy in infrastructure and they therefore have a limited ability to manage climate change impacts (Dupigny-Giroux et al., 2018). Adopting new technologies, modifying management practices, and changing which commodities are produced can help forestry and agricultural systems adapt; however, there are limits to adaptive capacity and more strategies need to be developed (Gowda et al., 2018).

Recent studies have emphasized the need to do more than reduce GHG emissions from fossil fuels if increasingly costly impacts are to be avoided. To achieve climate goals, we must also look for ways to remove carbon from the atmosphere and sequester it in biomass, soils, and products. Natural climate solutions (NCS), such as reducing tillage intensity, planting perennial grasses and trees, and setting aside land that sequesters carbon or limits GHG emissions can affect near-term GHG mitigation goals in cost-effective ways and enhance long-term ecosystem services. Within the United States, implementing NCS have the maximum potential to mitigate 21% of current net annual GHG emissions (Fargione et al., 2018). However, stakeholders from throughout Maine and the U.S. have determined that foresters and farmers need additional policies, tools, and incentives to adopt practices that promote carbon sequestration, GHG emissions reductions, and better forest and soil health at a scale that significantly contributes to climate change mitigation and adaptation.

There is a need for an accessible way for stakeholders to evaluate and prioritize the various practices that could be used to achieve GHG mitigation goals, and Maine-specific analyses will inform the state climate action plan, Maine Won't Wait (2020), and enhance effective implementation of NCS practices. To date, most NCS studies are at the global and national scale, and state-level estimates are often reliant on assumptions derived elsewhere that may not transfer well to Maine. The practices covered are also often typical of conventional forestry or agricultural systems. Moreover, Maine foresters and farmers may face unique implementation barriers important in the state that are not evident elsewhere. The analysis presented in this report attempts to address these considerations by helping to identify efficient, cost-effective solutions to improve forest and agronomic land management, reduce carbon-negative land use change, and promote soil health in Maine.

This report is part of the larger 'Maine Natural Climate Solutions Initiative' project which seeks to: (1) assess current practices to determine the degree to which foresters and farmers are using NCS; (2) determine the most cost-effective NCS for Maine; (3) understand key barriers of adopting NCS; and (4) generate information about which practices can be implemented on a broader scale.

The report is organized as follows. First, we present the general methodology for estimating potential impacts from implementing NCS across Maine. Next, we present the model baseline and results from a wide range of scenarios and practices applied to the state's forest and agricultural sectors. We then conclude the main report with a summary of the key findings. Two appendices provide additional detail on the study results and model input data.

2. Methodology

2.1 Estimating Costs and Benefits of GHG Mitigation

The main objective of this study was to estimate the GHG mitigation benefit and costs of implementing NCS practices in Maine's forest and agricultural sectors. ***First,*** we established a model 'baseline' or 'business as usual' (BAU) pathway that all other scenarios or pathways would be compared to or measured against. In this case, we assumed a continuance of current policy and practices that maintain the harvest, cultivation, and planting rates that have been apparent over the past decade. ***Second***, we defined the geographical and temporal scale of the baseline. The framework for this study focused on impacts to two sectors (agriculture and forests) across the entire state, with a key exception of some of the forest modeling, which utilized a case study approach for a block of nine million acres of managed forestland in the northern part of the state. In terms of temporal scale, forest impacts were measured through 2100 (80 years), while the agriculture sector impacts were measured over the next 20 years. ***Third***, we specified the environmental conditions that the model baseline should follow, namely the effect of climate change on biophysical growth and yield. In this analysis, the forestry modeling baseline assumed that Maine's climate would follow a low-emissions and impacts trajectory, specifically the Representative Concentration Pathway (RCP) 2.6. We did not assume any climate change impacts for the agricultural sector due to lack of data.

The next key aspect of designing a mitigation modeling study was to establish a list of potential NCS practices that could feasibly be implemented in Maine. During such a process, there is often a debate about what mitigation should be included, both from a biophysical and a socio-economic perspective. Policy constraints and concerns about land-based mitigation practices include ways to properly 'measure, monitor, and verify' that practices are being implemented correctly and whether issues with permanence, additionality, and leakage make the project a risky investment. The set of NCS practices that we opted to analyze in this report was decided based on a mix of expert input, data availability, and modeling capability. While this report is the most comprehensive analysis of NCS practices ever done for Maine, our list of opportunities that could be implemented across the landscape is not necessarily exhaustive.[2]

The last key aspect of the analysis was to estimate the cost and effectiveness of implementing the NCS practices under consideration. This is typically done using a suite of applications and methods that integrate both economic and biophysical modeling. Most of these models attempt to be empirically based but can be complicated by the complex nature of the land use sector. Implementing NCS practices across Maine's landscape is likely to accrue several costs and benefits relative to the baseline or BAU. Key benefits could include reduced GHGs or increased carbon sequestration, yield improvements, enhanced ecosystem resilience, cost savings from reduced expenditures, and other environmental benefits such as improved soil health and water quality (Figure 2). Key costs that may accrue include added capital, labor, and maintenance costs, land acquisition costs, yield (and revenue) reductions, and loss in harvestable area. The latter two can be considered opportunity costs because it is essentially the income that one is willing to forego to achieve the benefits associated with implementing the practice. All monetary values in this study are inflation adjusted and reported in 2017 real dollars.

Figure 3 provides an illustrative example of how the average benefits and costs of a given NCS practice are calculated, specifically the impact of shifting from intensive to reduced-till farming across 50,211 acres of potatoes planted in Maine. In this case, each acre of land converted to reduced till is estimated

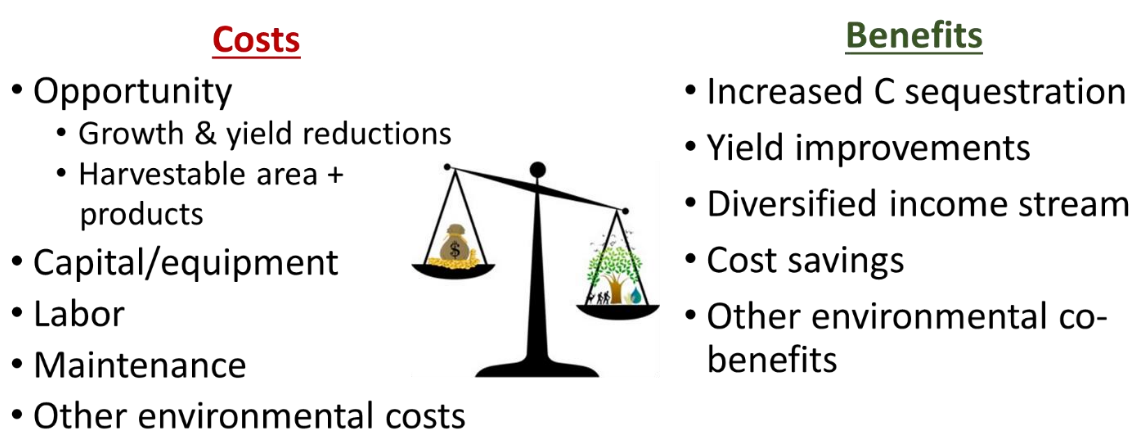

Figure 2. Key costs and benefits of implementing natural climate solutions relative to business as usual.

[2] E.g., resource limitations prevented us from analyzing the impact of implementing a range of intermediate silvicultural treatments on Maine's forests. This is a topic for future research.

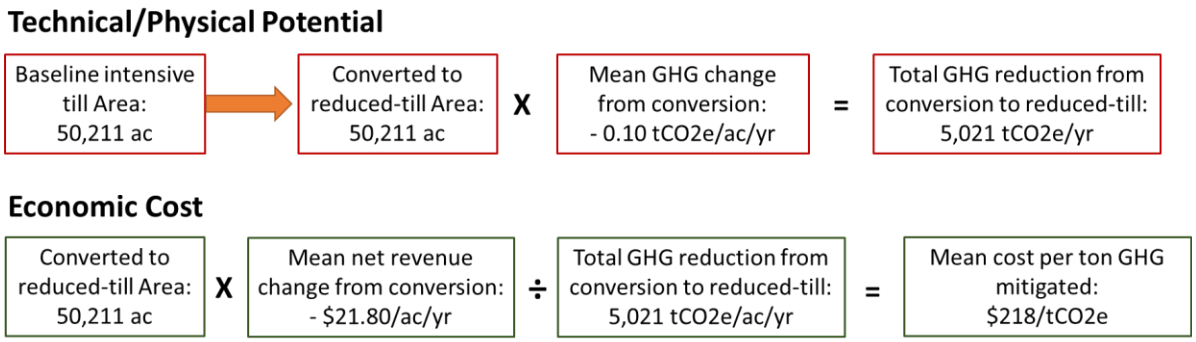

Figure 3. Hypothetical example of how to calculate biophysical potential and economic cost of converting all eligible Maine potato farms from intensive to reduced crop tillage.

to provide 0.10 metric tons of carbon dioxide equivalent (tCO_2e)[3] per year of additional carbon sequestration, equating to just over 5,000 tCO_2e/yr in total mitigation across the state. That amount of mitigation can then be used to estimate the total cost and/or the cost relative to their baseline practice by multiplying the total area converted by the mean net revenue (commodity output revenue minus new input costs such as additional labor) change, which equates to about $1.1 million per annum, or $21.80/ac. This figure can then be converted into the amount that an average potato farmer may be willing to accept to 'break even' by implementing this practice, which is quantified using the common mitigation cost metric of $/$tCO_2e$. In this example, that break-even carbon price for converting all eligible intensively tilled potato area in Maine to reduced till is estimated to be $218/$tCO_2e$. We replicated this methodology for the dozens of crop and forest management scenarios that we describe in detail below.

2.2 Forestry

2.2.1 Overview

Forests currently cover about 17.5 million acres or nearly 89% of Maine's area. The forest industry sector is statewide and multi-faceted and has provided an average of $8 billion/yr in economic impact over the past decade, while also supporting other important sectors of Maine's economy such as recreation and ecotourism. Furthermore, Maine's forests have been estimated to sequester the equivalent of nearly 70% of the state's annual gross greenhouse gas emissions from 2012-2017 (Domke et al., 2020; *Eighth Biennial Report on Progress Toward Greenhouse Gas Reduction Goals*, 2020), as carbon stored in new forest growth and harvested products is greater than the amount removed (Figure 4). However, significant changes to both the state's forests and forest industry are expected in the decades to come via shifts in market demand, distribution of landownerships, policy adjustments, and climate change. Furthermore, Maine's forest is in an ecotone between northern temperate and boreal forests with a broad mixture of species, with changing climatic conditions creating significant stress to forest health as most species are either at their northern or southern limit. As a result, we sought to analyze the potential impacts on Maine's forest carbon sequestration through 2100 under a range of different management regimes. Furthermore, we evaluated the impact of our assumptions via

[3] Forest carbon estimates in this study are reported in either tons carbon dioxide equivalent (tCO_2e) or tons carbon (tC). 1 tC = 3.67 tCO_2e, while 1 tCO_2e = 0.27 tC.

sensitivity analysis. This section provides an overview of how the modeling of forest natural climate solutions was conducted.

2.2.2 Forest NCS Practices/Scenarios

We adopted a staged modeling approach that included analyzing several different forestry practices with NCS potential. These were:

1. Extended Rotation: increased minimum stand age eligible for harvest.
2. Clearcut/Partial harvest distribution: increased percentage of the area harvested by clearcut vs. partial harvest.
3. Planting: added planting (also known as artificial regeneration) after clearcut with a 700-tree-per-acre mix of red and white spruce.
4. Set-aside: increased percentage of the available land base permanently excluded from harvested areas through 2100.
5. Triad approach: examined a mix of BAU rotations, clearcuts with planting, and increased set-asides.
6. Afforestation/reforestation: planted trees in eligible areas not forested since at least 1990.
7. Avoided Forest Conversion: held current forest area constant via renting land at cost of highest and best use if converted.

Stage 1 explored the impacts of these practices on aboveground carbon, harvested wood carbon, revenues, and costs using a mixed modeling approach. Practices 1-5 were modeled with LANDIS-II, a landscape-level dynamic forest ecosystem model covering more than 9 million acres of northern Maine (See Section 2.2.3). Many of the LANDIS-II modeled practices included more than one variant (Table 1). Practices 6 and 7 were estimated for the entire state of Maine based on a methodology that did not utilize the LANDIS-II model (See Section 2.2.4). Several of these practices were initially modeled and presented as preliminary results reported in the September 2020 Interim Report by Daigneault et al., 2020. This final report focuses on results from a second round of modeling for a subset of refined scenarios (Table 1). Here we integrate the results from both Stages 1 and 2 of the analysis.

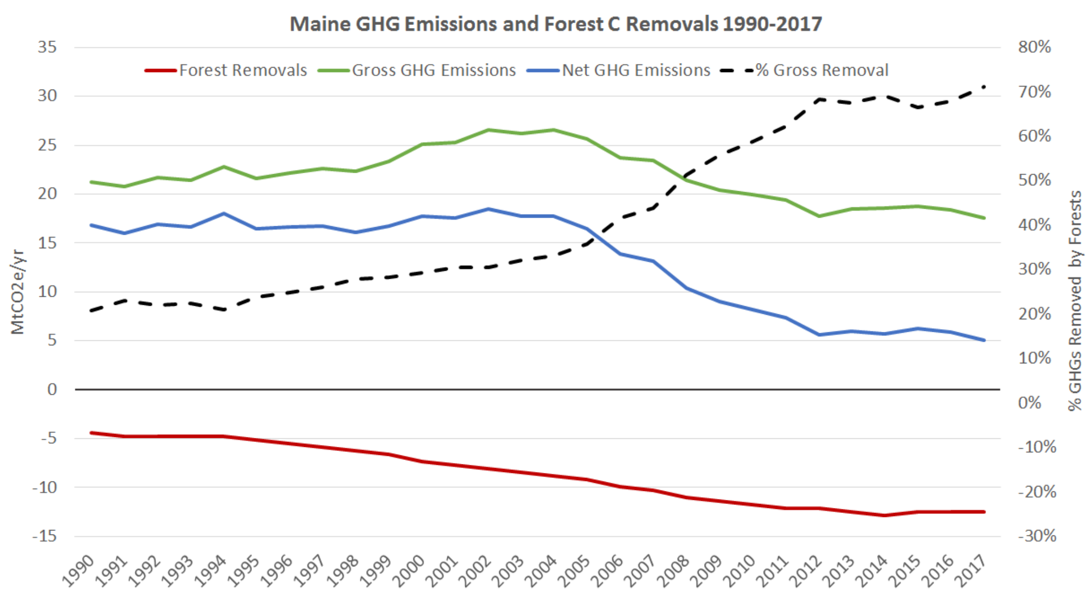

Figure 4. Maine GHG emissions and forest carbon removals, 1990-2017 (Source: Domke et al., 2020; Maine DEP, 2020).

Table 1. Complete set of forest NCS practices modeled with and without LANDIS-II. The subset of refined LANDIS-II scenarios included as part of Stage 2 modeling highlighted in green.

Scenario Focus	**Scenario Name**	**% Clearcut**	**Min. Stand Age**	**Plant after Clearcut**	**% Land Set Aside**
Landis-based Scenarios					
Baseline/BAU	BAU min 50	10	50	No	0
Extended Rotation	Min 85 years	10	85	No	0
	Min 100 years	10	100	No	0
Clearcut/Partial Harvest Dist.	35% Clearcut (CC)	35	50	No	0
	50% CC	50	50	No	0
Clearcut & Plant	35% CC, plant	35	50	Yes	0
	50% CC, plant	50	50	Yes	0
Set-aside forest land	10% set-aside	10	50	No	10
	20% set-aside	10	50	No	20
Triad Approach	35% CC, plant, 10% set aside	35	50	Yes	10
	35% CC, plant, 20% set aside	35	50	Yes	20
Non-Landis Scenarios					
Afforestation	Afforestation	10	50	No	0
Avoided forest conversion	Avoided conversion	10	50	No	0

2.2.3 LANDIS-Based Modeling

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 & He, 1999). 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.

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.

We used LANDIS-II to model the effects of alternative management strategies on the carbon dynamics of Maine's 13 most abundant tree species (Appendix B) between 2010 and 2100. Circa 2010, these 13 species comprised 86% of Maine's aboveground forest biomass. 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 5) encompassed approximately 9.1 million acres of primarily commercial forestland. Owners within this area are predominantly considered large (>10,000 acres) landowners and represent a diverse range of ownership types (e.g., family, high net-worth individuals, timber investment management organizations, real estate investment trusts, and non-profit organizations).

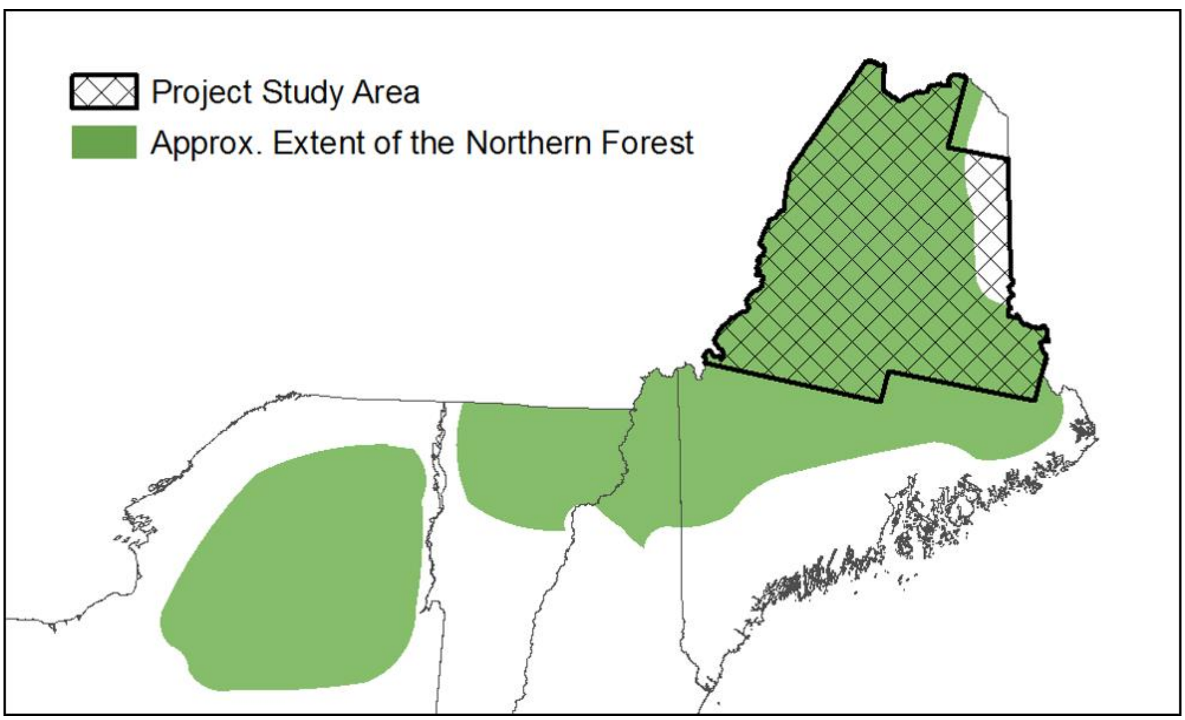

Figure 5. Project study area for forest landscape projections using LANDIS-II encompassed approx. 9.1 million acres of predominantly commercial forestland in northern Maine.

[4] Following the methods of Legaard et al., 2020

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 Succession module (Scheller & Mladenoff, 2004) to model forest growth and succession, the Base Wind module (Scheller et al., 2007) to model blowdown, and the HARVEST 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. To estimate future (2020-2100) productivity for each species we incorporated monthly, downscaled climate projections for our study area. Gridded projections were based on the AO (Atmospheric-Oceanic) variant of the Hadley global environment model v2 (HADGE-AO) under a low-emission (RCP 2.6) and high-emission (RCP 8.5) scenario and obtained from the USGS Geo Data Portal (*USGS Geo Data Portal*, 2020).

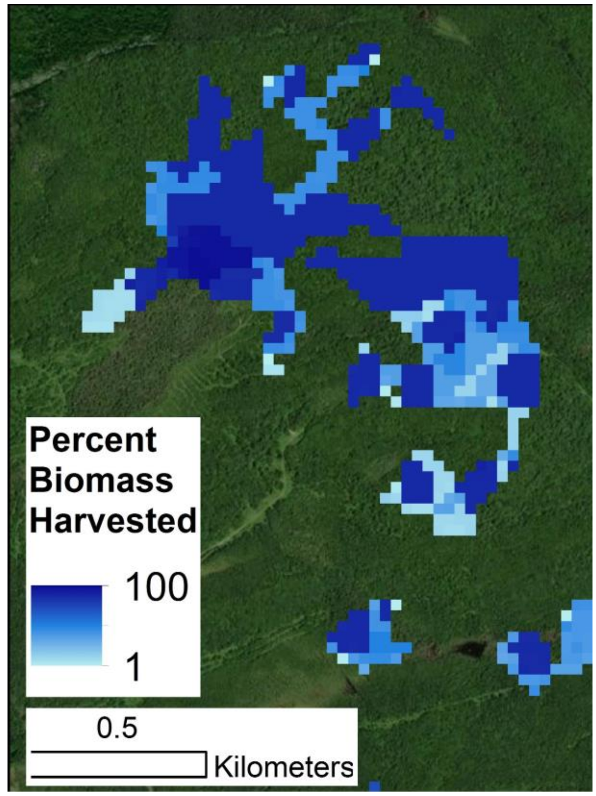

Figure 6. Example of forest biomass removal (30m resolution) within a partial harvest modeled using LANDIS-II.

We modeled two harvest prescriptions: clearcut and partial harvest. Partial harvests were designed to be spatially variable at the stand level, approximating a generalized prescription that includes a combination of complete (100%) overstory removal (within harvester trails) and partial overstory removal targeting mature/merchantable (30-60% removal) or overmature (100% removal) trees in the areas adjacent to the trails. All species were eligible for harvest. The partial harvest prescription was calibrated to remove an average of 50% of the live biomass overall from a stand (Figure 6).

Our baseline or business-as-usual (BAU) scenario emulated the average annual harvest rate within the study area (i.e., 1.9% or approximately 145,000 acres harvested per year), as estimated from a Landsat-derived time series of forest disturbances (2000-2010) (Legaard, 2018). Within LANDIS-II, although selection of stands to harvest is ultimately randomized, the pool of stands available for harvest can be constrained based on, for example, stand forest type or age. For the BAU scenario (hereafter referred to as 'BAU min50' or 'BAU') we set the minimum stand age eligible for harvest at 50 years old, which follows historical trends for Maine timber harvests. Under the BAU min50 scenario, 10% of the total annual harvest area was treated by clearcut (i.e., approximately 14,500 acres of the total 145,000 acres harvested per year) and 90% by partial harvest (i.e., approximately 130,500 acres per year) distributed broadly across the 9.1 million acre study area.

In LANDIS-II we adjusted (1) stand selection criteria, (2) proportion of area harvested (clearcut vs. partial harvest), or (3) forested area available for harvest to model the different NCS practices (Table 1). To model forest management with extended rotation, we increased the minimum stand age eligible for harvest from 50 years old (BAU min50 scenario) to 85 or 100 years old. We increased the percentage of total area harvested by clearcut from 10% to 30% or 50% to better understand the NCS potential of incremental increases in intensive management. For those scenarios, wood supply was held constant by proportionally reducing total harvest area, assuming on average 1 acre of clearcut would result in the same volume harvested as 2 acres of partial harvest. We also ran these scenarios with and without planting within clearcut areas. In Stage 1 of our modeling, we applied simple criteria based on owner type to model the impacts of increased set-asides. In Stage 2, following stakeholder feedback, we instead mapped all riparian habitat in our study area (including 250-foot buffers around great ponds, rivers, and wetlands greater than or equal to 10 acres and 75-foot buffers around streams) and excluded those areas from future harvesting. In total, riparian habitats represented ~20% of the available forested land base.

Over the course of a simulation, LANDIS-II 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 LANDIS-II 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 NCS scenario. In addition, we tracked a variety of biodiversity indicators and compared their statuses (ca. 2050 and 2100) under the NCS scenarios to the baseline scenario. We chose indicators that represented the range of forest developmental stages (early-, mid-, and late-successional forest) and highlighted regionally important forest types (spruce-fir and northern hardwood).

1. **Late-successional (LS) forest**: We determined the change in late-successional (LS) forest area for both spruce-fir forest (>75% balsam fir and spruce spp. relative abundance) and northern hardwood forest (>75% sugar maple, yellow birch, American beech relative abundance). Forests 100+ years old are considered critical to maintaining forest biodiversity because of the unique structures (e.g., large trees, snags, and vertical structural diversity) they provide and obligate species they support (Whitman & Hagan, 2007).
2. **Mid-successional (MS) forest**: Well-stocked mid-successional forest (40-100 years old) provides important habitats for wildlife including the American marten. Marten prefer tall, structurally complex forest. Previous research at the University of Maine indicates that their use of forest can be predicted based on basal area (>80 ft^2/ac; Payer & Harrison, 2003). This area-sensitive species has also been evaluated as a potential umbrella species, with preliminary results suggesting that conservation of marten habitat would benefit >70% of Maine's forest vertebrates.
3. **Early-successional (ES) forest**: Populations of many bird species associated with early-successional hardwood forest are declining in the U.S. following an earlier peak that came as a result of forest regrowth after agricultural abandonment and forest conversion has also reduced available early-successional habitats. Timber harvesting creates early-successional forest conditions by removing mature trees and restarting the successional process, which benefits songbirds that use shrub or hardwood sapling habitats (basal area <59 ft^2/ac; (Hagan & Whitman, 2004; Simons et al., 2010)). Similarly, regenerating spruce-fir forest provides

important habitat for the snowshoe hare, which is considered a keystone species in the northern boreal forest. The presence of habitat that supports high densities of snowshoe hares (15- to 40-year-old-forest with >50% spruce-fir relative abundance) is considered essential for the conservation of the federally threatened Canada lynx.

2.2.4 Non-LANDIS Forest NCS Modeling

Two of the forest NCS assessments were estimated for the entire state of Maine based on a methodology that did not utilize the LANDIS model: a) afforestation/reforestation[5] of marginal non-forest land that has not had trees on it for several years, and b) avoided conversion of current forestland that is considered under threat of being changed into developed or agricultural use.

Afforestation

The afforestation estimates were derived based on methods from Cook-Patton et al. (2020) that evaluated the potential for the contiguous U.S. at a high spatial resolution. Locations for this NCS were initially constrained to areas where forests with greater than 25% tree cover historically occurred but had less than 25% tree cover for several years. Additional assumptions excluded all cropland not located in areas with challenging soil conditions[6], all developed land not designated in the National Land Cover Database as 'open space', and land designated as protected or wilderness areas. In total, we estimated that about 360,000 acres of land in Maine met the criteria for afforestation, with 65% of the area coming from pasture/grassland, 25% from open space, 10% from cropland, and the remainder from 'other' land covers. Afforested land was assumed to be established primarily through natural regeneration and included a mix of tree species already growing in Maine. Annual tree biomass and carbon sequestration estimates from afforestation were derived from FIA. Mitigation costs included opportunity cost of the alternative land use (due to lost future revenue) as well as stand establishment and maintenance costs. Pasture and cropland values were based on USDA Cropland Reserve Program (2020) rental rates (where land has typically 'marginal' productivity), while developed land values were obtained from Davis et al. (2020).

Avoided Forest Conversion

Avoided forest conversion (i.e., deforestation) estimates were derived from methods similar to Fargione et al. (2018). The land use change and forest carbon impacts were provided by Clark University's Biogeosciences Research Group.[7] Future conversion was based on extrapolating historical trends based the 2016 National Land Cover Database (NLCD)[8] forward over the next century. The forest area and carbon stocks and fluxes were the National Forest Carbon Monitoring System (NFCMS) 30-m scale dataset published on ORNL DAAC,[9] and described in Gu et al. (2019), and aggregated to the county-level.

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[5] In this report, we use afforestation and reforestation synonymously, noting that the practice only targets land that has been forested in the past.
[6] Areas with challenging soil conditions were identified using land capability classes 4e, 5w, 6, 7, or 8 in the Gridded Soil Survey Geographic Database (https://gdg.sc.egov.usda.gov/).
[7] https://wordpress.clarku.edu/cwilliams/
[8] https://www.mrlc.gov/national-land-cover-database-nlcd-2016
[9] https://doi.org/10.3334/ORNLDAAC/1829

Forests converted to development or agricultural land were assumed to have two sources of carbon losses (i.e., emissions), (i) the removal of aboveground growing stock, and (ii) the foregone sequestration had the forest continued to grow. According to NLCD, approximately 5,000 acres of land were converted to development or agricultural land in Maine each year between 1990 and 2009, with about 80% of the conversion going to development (Table 2). Further, these forests were estimated to have mean carbon stocks of 215 tCO_2e/ac, which would be the amount of carbon loss mitigated if these areas were not converted (Figure 7). Costs of mitigation included opportunity costs of land sale, based on Nolte (2020). Landowners who are compensated for not converting their forest to other uses would be paid initially for maintaining their existing carbon stock as well as the additional carbon that could be accrued on their stand in the years after the initial payment (i.e., additional carbon sequestration).

Table 2. Average annual Maine forest loss to development and agriculture by county (1990-2009).

County	**Forest Area Lost to Development (ac/yr)**		**Forest Area Lost to Agriculture* (ac/yr)**		**Total Forest Area Loss to Development and Agriculture (ac/yr)**	
	1990-1999	2000-2009	1990-1999	2000-2009	1990-1999	2000-2009
Androscoggin	126	112	71	40	197	153
Aroostook	649	682	376	245	1,025	927
Cumberland	351	393	71	44	422	438
Franklin	137	233	27	18	164	251
Hancock	111	161	34	36	145	197
Kennebec	89	94	46	33	134	127
Knox	47	54	23	22	70	76
Lincoln	30	34	11	12	41	46
Oxford	274	313	57	40	331	353
Penobscot	451	541	89	78	540	619
Piscataquis	384	408	11	16	395	424
Sagadahoc	33	36	7	5	40	42
Somerset	574	468	41	32	616	500
Waldo	65	63	56	28	120	91
Washington	289	401	170	120	459	521
York	324	392	75	46	398	438
Maine Total	**3,933**	**4,386**	**1,164**	**816**	**5,098**	**5,202**

** includes cultivated crops, hay, and pasture*

2.2.5 Forest Carbon and Cost Estimation

Carbon sequestration from growing stock was primarily estimated using FIA data. In addition to evaluating impacts of different practices on aboveground growing stock of biomass and carbon, we also estimated the potential change in wood carbon stored in various harvested wood products (HWP) and landfills over time, as some products can store carbon for decades or centuries (Figure 8). The HWP and landfill C estimates were derived using the methods from Smith et al. (2006), and averaged over a 100-year period using the weighted-average of the historical harvests of biomass (19%), pulpwood (48%), and sawlog (33%) removals. This approach yielded a HWP plus landfill equivalent to 26.4% of the total biomass/carbon removed/harvested from the stand being stored on average over a 100-year period (Bai et al., 2020; Hennigar et al., 2013). The remaining carbon removed was assumed to be emitted

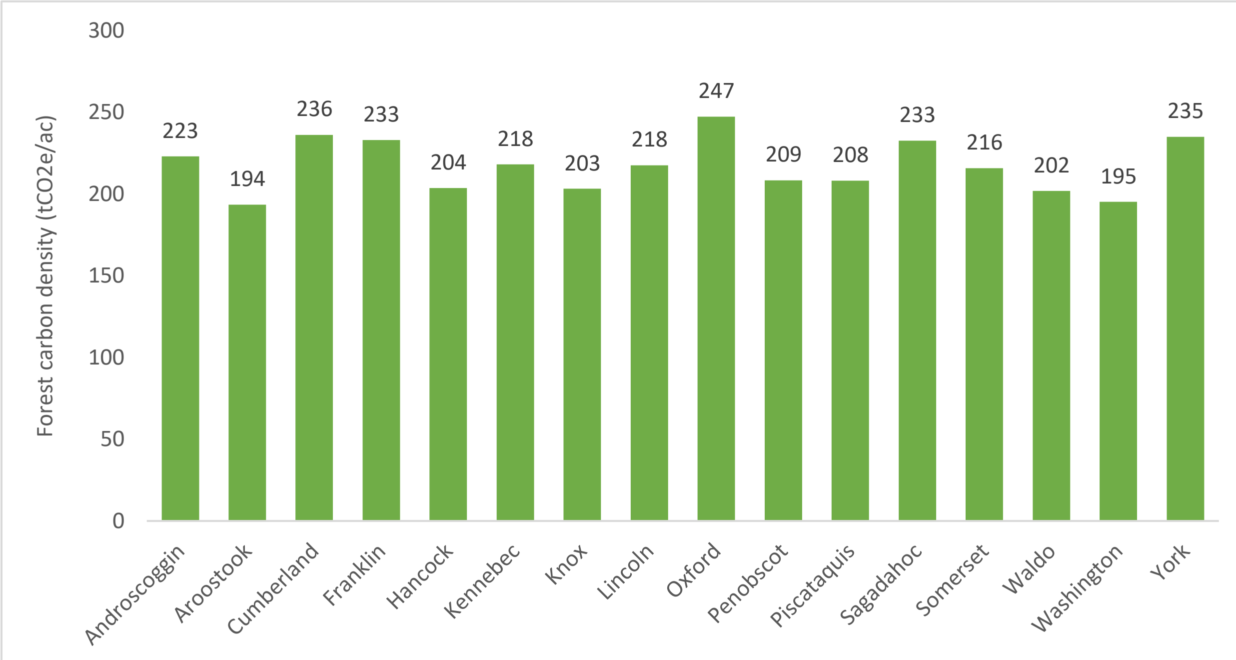

Figure 7. Mean density of forest carbon (tCO_2e/ac) mitigated from avoided conversion of forest to development and agriculture by county, based on NFCMS estimates.

immediately, primarily as biomass energy or mill residues (Smith et al., 2006). For this analysis, we report the 'total' forest carbon sequestration in any given year as the sum of aboveground forest growing stock, HWP, and landfill carbon.

Economic benefits and costs from implementing different types of forest practices were based on four primary components: (a) harvest revenue, (b) land acquisition costs, (c) planting costs, and (d) opportunity costs. Harvest revenues were estimated by multiplying the biomass harvested by mean state stumpage price for each product harvested (Maine Forest Service, 2020). Planting costs were assumed to be a mix of seedlings ($0.37/plant) planted at a density of 800 trees per acre ($296/ac) and site prep which included two spray applications ($250/ac), for a total of $546/ac. Land acquisition costs and annual rents varied by current or highest and best use and were acquired from USDA (Cropland Reserve Program Statistics, 2020) and Davis et al. (2020). Finally, opportunity costs were estimated as the change in harvest and other land use revenue relative to the baseline or business as usual case. We note that there are cases where revenues can potentially be higher than the BAU estimate, such as plantations from stands that were initially naturally regenerated.

2.2.6 Sensitivity Analysis

The LANDIS-based scenarios already evaluated the effect of varying minimum stand harvest age, percentage of land designated as no-harvest set asides, the distribution of partial and clearcut harvesting, and whether clearcut stands are artificially regenerated (i.e., planted). We conducted additional sensitivity analyses to assess the impact of some of the core assumptions on our model estimates. The first sensitivity analysis evaluated the effect of climate change on forest growth and sequestration in the LANDIS model. In this case, we adjusted the climate change input files from RCP 2.6 to 8.5, which has a higher climate variability compared to historical trends. The set of sensitivity analyses

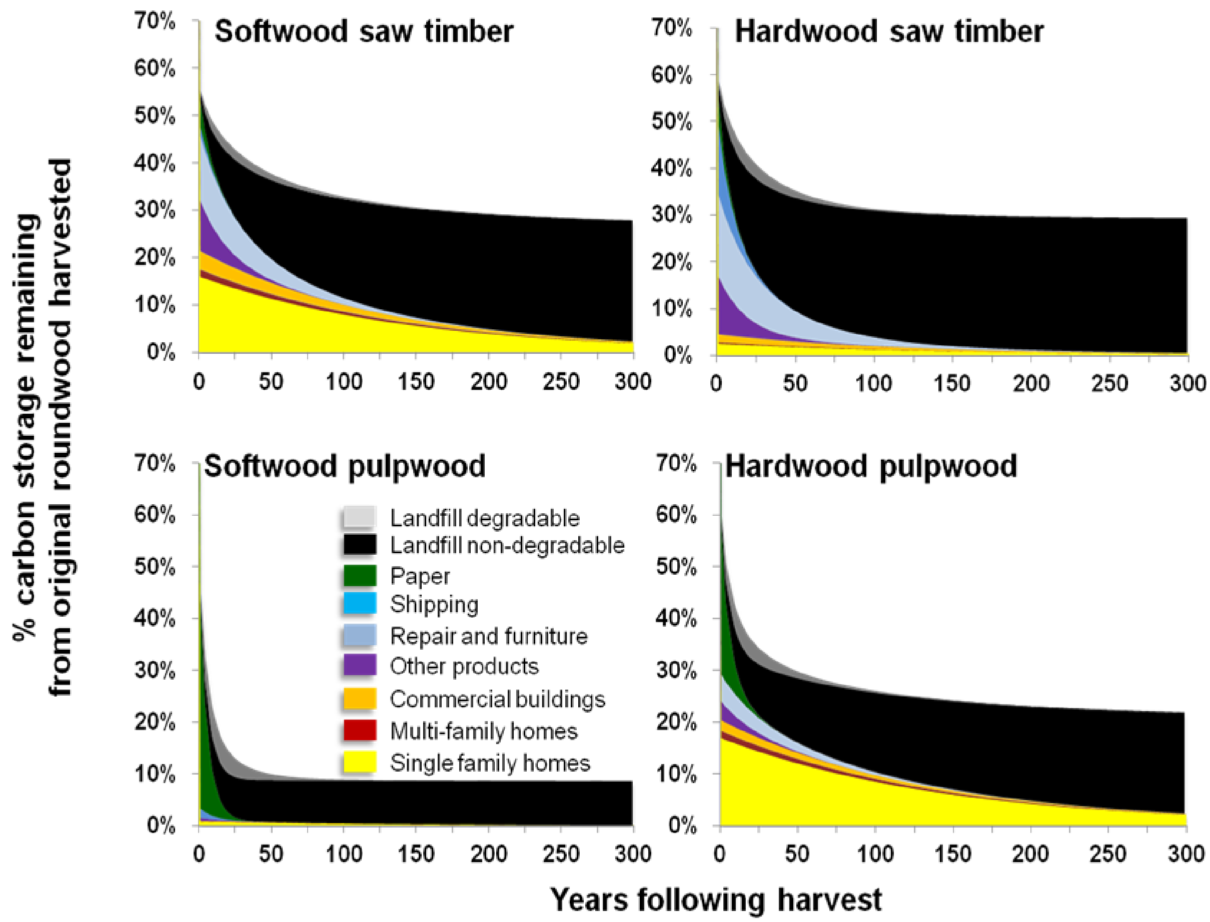

Figure 8. Percent carbon storage in harvested wood product and landfill carbon following harvest (Source: Hennigar et al., 2013; Smith et al., 2006).

that we conducted varied the harvest revenue, planting, and land acquisition costs to be +/- 25% of the original assumption. Taking this approach allowed us to assess the relative importance of various input assumptions on the total and break-even costs of the different scenarios. Second, we conducted a sensitivity analysis that adjusted the stumpage price and planting costs that landowners may face under different stand and market conditions by a factor of ±25% compared to our core assumptions.

2.3 Agriculture

2.3.1 Overview

The agricultural sector in Maine emitted 0.38 million tons of CO_2e ($MtCO_2e$) in 2018, approximately 2% of total state emissions (17.51 $MTCO_2e$) across all reported sectors (Maine DEP, 2020). The bulk of the emissions are from livestock (via enteric fermentation and manure management), with dairy contributing 48% of the total agricultural sector emissions (Figure 9). Agriculture, excluding forestry, fishing, and aquaculture, encompasses 1.3 million acres (USDA NASS, 2019), has an annual economic impact of $3.8 billion, supports 25,000 jobs, includes 8,000 farms, and represents about 5% of the state's GDP (Lopez et al., 2014). The primary crops grown in Maine include potatoes, blueberries, hay,

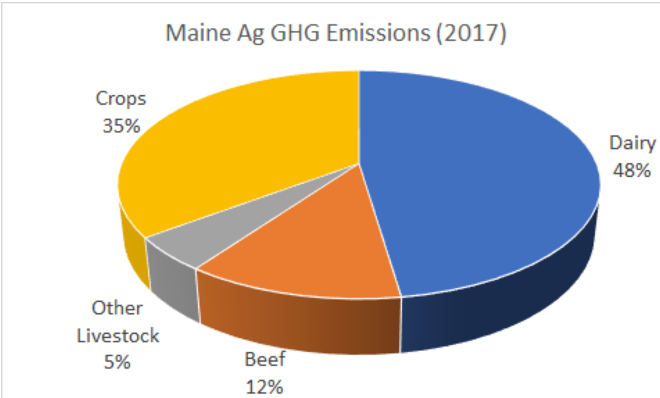

Figure 9. Maine Agricultural GHG Emissions by major enterprise (Source: DEP, 2020).

and grains including corn, barley, and oats. These crops represent 76% of the total harvested acreage in 2017. Dairy and other livestock commodities represent over 20% of farm sales (USDA NASS, 2019). Although 90% of Maine is covered by forest, agriculture remains an important part of Maine's cultural identity, local economies, and current and future food security.

2.3.2 NCS Practices/Scenarios

Agriculture represents a smaller component of the Maine economy relative to forestry, but changes to agricultural management practices can also contribute to state-wide climate change mitigation while enhancing adaptation and resilience in the agricultural sector. Agricultural natural climate solutions have been identified as an important strategy for improving farm viability by increasing carbon storage, limiting greenhouse gas emissions, improving soil health and water quality, and increasing yields and profits per acre. NCS practices can be adopted by farmers regardless of their production methods or the size of their operations. We analyzed a range of agricultural NCS that were already being implemented on some of Maine's farms or were determined to be feasible given Maine's climate and farming conditions. These practices are summarized in Table 3. Additional details are provided below and in Appendix B.

Table 3. Overview of agricultural NCS practices considered for this analysis.

Practice	Overview	Application
	Cropland and Grassland NCS	
Cover cropping	Permanently implement cover cropping as part of farm system to enhance soil organic carbon accumulation, reduce erosional soil losses, enhance water infiltration, and reduce N losses (N_2O, NO_3).	Potatoes, corn, other grains, vegetables
Intensive to reduced-till	Permanently switch to reduced till farming that is limited to shallow soil disturbance to reduce C loss.	Potatoes, corn, other grains, vegetables
Reduced to no-till	Permanently switch to no-till farming for enhanced soil organic carbon accumulation through less soil disturbance.	Corn, other grains, vegetables
Intensive to no-till	Permanently switch to no-till farming for enhanced soil organic carbon accumulation through less soil disturbance.	Corn, other grains, vegetables
Biochar amendment	5.9 t/ac biochar broadcast applied to soil in year 1 of a 20-year cycle for enhanced soil C sink, improved soil health, and reduced GHG losses and nutrient runoff.	Potatoes, corn, other grains, vegetables, hay, blueberries, apples

Practice	Overview	Application
Manure amendment	Substitute manure and compost for fertilizer to reduce CO_2, CH_4, and N_2O losses.	Potatoes, corn, other grains, vegetables, hay, blueberries, apples
Natural mulch	Apply straw or crop residue as a mulch to enhance soil organic carbon and reduce erosional soil losses.	Blueberries, vegetables
Perennial set-asides	Permanently convert crop and pasture to no-harvest set-aside with perennial grasses and woody plants. Soil C enhanced through reduced disturbance.	Potatoes, corn, other grains, vegetables, hay, fruit
Riparian planting	Plant 35-ft buffer of trees, shrubs, and grass along streams running along marginal cropland and pasture.	Potatoes, corn, other grains, vegetables, hay, fruit
Dairy Manure Management		
Large Complete Mix Anaerobic Digester with electricity generation	CH_4 emissions are reduced using a large model low-rate digester in which digestate is actively mixed in a heated tank with airtight cover. Digestate is gradually displaced by incoming manure substrate.	One digester per 2,500 cows
Covered Lagoon/Holding Pond Anaerobic Digester	Passive digester in which an impermeable cover and pipe system traps and collects CH_4 for reduced emissions. Technology is simple and well-established, but supplemental heat may be needed in Northern climates.	One digester per 300 cows
Solid-liquid separation (SLS)	Process for separating dairy solids from liquids, either to reduce manure transit costs and associated emissions or as a pre-treatment for anaerobic digestion.	Active SLS with a screen separator, one SLS per 1,000 cows
Small Complete Mix Anaerobic digester (AD) with electricity generation	CH_4 emissions are reduced using a small model low-rate digester in which digestate is actively mixed in a heated tank with airtight cover. Digestate is gradually displaced by incoming manure substrate.	One digester per 300 cows
Plug Flow Anaerobic digester (AD) with electricity generation	CH_4 emissions are reduced using a low-rate digester in which incoming high-fiber substrate displaces and moves digestate through the system, usually without active mixing. Consists of a long heated tank with airtight cover.	One digester per 300 cows

2.3.3 Analytical Approach

The agricultural NCS modeling was centered on a financial and agronomic response analysis that quantified the economic impacts (revenue, cost, etc.) of implementing NCS relative to the change in yields, GHG emissions, and carbon sequestration in comparison to the business as usual (BAU) or baseline case over the next 20 years. In this analysis, the baseline assumed that current yields and areas were held constant over time.[10] The NCS practices included cover crops, reduced-till, no-till, biochar

[10] We were unable to consistently model the impact of climate change on crop yields due to lack of data.

amendments, manure amendments, several manure management practices, and perennial set-asides (Table 3). GHG emissions factors and sequestration for the model baseline and NCS practices were informed by an extensive literature review. Most baseline emissions factors were based on estimates from Poore and Nemecek (2018). Crop NCS mitigation factors were primarily estimated using the COMET Planner tool (Swan et al., 2020), while dairy manure management factors were primarily derived from the EPA Ag Star Livestock Anaerobic Digester Database (EPA, 2020).

All impacts were estimated at the major crop, NCS practice, and county-levels. Most of the results in the main report are presented at the aggregate state level; further details can be found in Appendix B. Baseline and current NCS practice area by major crop category in Maine (Table 3) were drawn or extrapolated from data provided in the 2017 USDA NASS Census of Agriculture (2019). Baseline crop production area values were: 68,725 acres of harvested potato, 38,660 acres of lowbush blueberry, 174,231 acres of hay and haylage, 54,247 acres of corn grown for grain and silage, 52,858 acres of other grains, 7,441 acres of apples and other perennial crops, and 12,305 acres of harvested vegetables other than potato. In developing Table 4, several assumptions were made. All area currently in no-till production (21,676 acres) was assumed to be in silage or grain corn systems.[11] Area in reduced tillage (37,967 acres) was split between potato, other vegetables, corn, and other grains.[12] Current land in cover crops (94,881 acres) was assumed to be primarily associated with multi-year potato and other

Table 4. Estimated Baseline Area in NCS Practices for Maine (acres).

Major Crop	Total Crop Area*	No-till	Reduced tillage	Cover crop	Biochar Amend	Amend w/ manure	Natural mulch	Convert to perennial set-aside	Riparian Buffer
Potato	68,725	X	18,514	49,772	0	0	X	0	0
Lowbush blueberry	38,660	X	X	0	0	X	0	X	0
Hay & haylage	174,231	X	X	X	0	45,629	X	X	0
Silage & grain corn	54,247	21,676	0	0	0	29,314	X	0	0
Other grains	52,858	0	13,439	39,419	0	0	X	0	0
Apples & other perennials	7,441	X	X	X	0	X	X	X	0
Other vegetables	12,305	0	6,014	5,690	0	X	601	0	0
Total Study Area	408,467	21,676	37,967	94,881	0	74,943	601	0	0

**= not all crop area is currently in a NCS practice; More than 1 practice can be implemented on a given acre (e.g, no till and cover crop); X = not eligible for NCS practice.*

[11] Informed by personal communication with E. Mallory and J. Jemison, Spring 2020.

[12] Definitions of reduced tillage vary by system and may not align perfectly with the NRCS definition. Based on data from an organic vegetable farmer focus group (Daigneault et al., unpublished data, February 26, 2020), we assumed a large fraction of vegetable land (50%; 6,104 acres) is employing some form of reduced tillage. We assumed a smaller fraction of corn (25% of the amount not in NT; 2,724 acres) and other grains (25%; 9,855 acres) is employing reduced tillage, and the remainder (13,361 acres) represents a reduced tillage practice in potatoes such as one-pass hilling.

vegetable system rotations; a small amount was assumed to be undersown in grains.[13] Current adoption of biochar amendments was assumed to be zero based on our understanding that this practice is uncommon at present.[14] The acreage on which nitrogen fertility is offset with dairy manure amendment (74,943 acres) was split between corn and hayfields such that a large fraction of silage and grain corn (90%; 29,314 acres) was assumed to have implemented this practice, with the remainder (45,629 acres) allocated to hay and haylage.[15] We assumed current mulch adoption on 0.3 acres of blueberries and 601 acres of vegetables other than potato.[16]

2.3.4 Agricultural Enterprises

The following section briefly describes the farm systems that we included in our analysis. We constructed representative cost budgets for the primary crops grown in Maine based on enterprise farm budgets for Maine or New England and expert consultation. Table 5 summarizes the per-acre yield, price, revenue, and cost for each agricultural enterprise as well as net revenue and net GHG emissions. Price per unit was estimated from a five-year average of the commodity's price in Maine from 2012-2017 (*Crop Values Annual Summary*, 2020). Detailed budgets and accompanying assumptions are included in Appendix B. The methodology and estimates for calculating net GHG emissions are also explained in Appendix B.

Table 5. Key Maine agricultural enterprises baseline farm financial and GHG input data.

Enterprise	Yield (unit/ac/yr)	Price ($/unit)	Revenue ($/ac/yr)	Cost ($/ac/yr)	Net Revenue ($/ac/yr)	Net GHG (tCO_2e/ac/yr)
Hay	6 tons	$165	$992	$323	$670	0
Potato	310 cwt	$10	$3,243	$3,084	$158	2.11
Blueberries	4,445 pounds	$0.47	$2,102	$1,735	$367	0.32
Wheat	45 bushels	$19	$844	$312	$532	1.03
Corn	100 bushels	$4	$369	$574	-$205	1.21
Barley	48 bushels	$5	$233	$373	-$139	0.18
Vegetables	varies	varies	$17,423	$12,223	$5,200	1.58
Apples	30,244 pounds	$0.31	$8,196	$5,966	$2,230	2.24
Dairy	158 cwt	$23	$3,567	$4,442	-$875	6.19

Apples

There are 449 farms with apple orchards in Maine, covering 2,668 acres. 38% of these orchards are smaller than one acre, and another 39% are between one and five acres in size (USDA NASS, 2019). Soil amendments with biochar and manure are NCS practices that can be implemented in orchards. We

[13] We assumed a small fraction (5%; 1,971 acres) of other grains are currently undersown with a cover crop.
[14] Daigneault et al., unpublished data, January 23, 2020; S. O'Brien, unpublished data, Fall 2019.
[15] Though many diversified vegetable farms also utilize manure as a soil amendment, this use was excluded from the present analysis, which assumed on-farm use of manure for forage and feed production by commercial dairies.
[16] Blueberry estimate from L. Calderwood, unpublished data, April 2021; vegetable estimate is based on an assumption of 5% current adoption on vegetable acreage other than potato.

estimated that, on average, a typical apple system made $8,196/bearing-fruit-acre (bfa) in revenue and had $5,966/bfa in total costs. As a result, the system produced $2,230/bfa in net revenue per year. Additional information about the apple system is available in Appendix B.

Blueberries

Approximately 38,000 acres of farmland in Maine are in wild or lowbush blueberry production, of which 850 acres are certified organic. Blueberries have a two-year production cycle such that approximately half of this total acreage is harvested per annum. Between 54 and 70 million pounds of blueberries are produced annually in Maine (Drummond et al., 2009; Rose et al., 2013; USDA NASS, 2019). Blueberry pricing has been a challenge for the industry in some recent years, with wholesale prices for conventional blueberries falling between $0.27-$0.75/lb between 2012 and 2018 (Calderwood & Yarborough, 2019). We estimated that an average blueberry system made $2,102/ac in revenue and had $1,735/ac in total costs. As a result, the system produced an average of $367/ac in net revenue per year. There is growing interest in value-added lowbush blueberry products, which may represent an opportunity for growth and improved economic stability in this industry. Additional information about the blueberry system is available in Appendix B.

Dairy

There are approximately 450 farms with dairy cows in Maine, a majority of which have herd sizes of fewer than 50 cows. The current 218 commercial-scale dairy farms house an estimated 28,000 cows, or an average of 130 cows/commercial farm.[17] Economic risks from market price fluctuations are offset for conventional dairies through the "tier program" (Drake, 2011), while pricing for organic milk is usually set in advance by 2- to 3-year contracts. About 30% of Maine dairy farmers are certified organic, with organic milk making up 7% of milk volume produced. Dairy cows are fed a roughage-based diet of forage, hay, and corn silage that is generally locally produced. In addition, grazing is common during the summer, and diets may be supplemented with concentrate. While manure represents a resource that can be used as part of integrated farm systems, storage during winter and mud season is a necessity. Land access is a major limiting factor to dairy production in Maine, in part because the lack of contiguous fields raises costs of manure transport.[18] Assuming a wholesale market, we estimated that, on average, a typical dairy farm made $3,567/cow in revenue and had $4,442/cow in total costs. As a result, the system produced -$875/ac in net revenue per year for the 2012-2017 timeframe.[19] Additional information about the dairy system is available in Appendix B.

Grains (barley, corn, and wheat)

Several types of grains, including grain and silage corn, barley, and wheat, are grown in Maine. These crops are primarily grown as feed for livestock and/or as part of rotational cropping systems. There has long been a market for malting barley, in addition to which there are now expanding markets for wheat. Several NCS practices can be implemented for grains, including no-till, reduced tillage, cover crops, and

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[17] R. Kersbergen, personal communication, Spring 2020.

[18] R. Kersbergen, personal communication, Spring 2018.

[19] N.B., the negative net revenue for dairy over the 5 year period of our data may be due to milk prices being lower than average over a longer historical period and/or the set of fixed costs that we accounted for, which may not be relevant for all Maine dairy farms.

soil amendments. We estimated that, on average, the net revenue for barley, corn silage, and wheat were -$139/ac, -$205/ac, and $532/ac, respectively. Acting as rotation crops in a potato system, barley and wheat function similarly to cover crops, requiring less intensive management and allowing soils to 'rest.' Additional information about each of these grain systems is available in Appendix B.

Hay

According to USDA NASS, 175,231 acres of farmland in Maine are used for hay and haylage (2019). Most hayfields are perennial sods consisting of clovers and grasses including bluegrass, orchard grass, quackgrass, and timothy. Periodic additions of lime are needed to reduce acidity, which helps to manage weeds and maintain hayfield productivity (Kersbergen, 2004). More intensive management of hayfields including occasional tillage, re-seeding of desired species, and fertility applications is also common for some applications (Hall, 2003). Hayfields are inherently no- or low-tillage production systems. Additional NCS practices that might be applicable in managed hayfields include strategic integration of organic amendments including manure or biochar into production. We estimated that, on average, a typical hayfield system made $992/ac in revenue and had $191/ac in variable costs and $132/ac in annualized fixed costs. As a result, the system produced $670/ac in net revenue per year. Additional information about the hay system is available in Appendix B.

Potatoes

Potatoes are a high-value crop, but they are also expensive to grow.[20] Approximately 50,000 acres of potatoes in Maine were grown in 2017 (USDA NASS, 2019) for three key markets: processing (approximately 30,000 acres), seed (approximately 11,000 acres), and tablestock (approximately 9,000 acres).[21] Most growers are using a 2:1 rotation with one year of potatoes and two years of a much less valuable grain or unharvested cover crop. Potato cropping involves key vulnerable periods with respect to potential soil erosion and loss of organic matter. The multiple tillage/cultivation passes inherent to potato planting and hilling are harmful for soil organic matter retention and soil structure. We estimated that, on average, a typical potato system made $3,243/ac in revenue and had $1,291/ac in variable costs and $347/ac in annualized fixed costs. As a result, the system produced $1158/ac in net revenue per year. Additional information about the potato system is available in Appendix B.

Diversified vegetable farm

This farm type is by nature diverse, often growing a wide variety of crops in complex multi-year rotations. According to USDA NASS data there were 881 Maine farms (not including potato farms) growing fresh market vegetables harvested for sale in 2017. Some of the prevalent crops are snap beans, potatoes, peppers, squash, sweet corn, and tomatoes (2019). Diversified vegetable systems usually rely on regular tillage both for weed control and preparation of a seedbed for planting (Myers, 2008). However, reduced-till practices are possible and of interest to growers, so reduced-till and perhaps adoption of no-till in some cropping sequences represent possible NCS. Many diversified vegetable farmers use cover cropping, but their use of the practice is sometimes constrained by cost of seed as well as limited acreage and the opportunity cost of taking land out of production.[22] Further

[20] J. Jemison, personal communication, February 2018
[21] J. Jemison, personal communication, February 2018.
[22] R. Clements, unpublished data, 2019.

adoption or increased intensity of cover cropping is likely feasible in these systems with altered incentive programs. We estimated that, on average, a typical diversified vegetable system made $17,423/ac in revenue and had $7,104/ac in variable costs and $5,119/ac in annualized fixed costs. As a result, the system produced $5,200/ac in net revenue per year. Additional information about the diversified vegetable system is available in Appendix B.

2.3.5 NCS Mitigation Costs and Effectiveness by Practice

Each NCS practice was assessed for its ability to reduce GHG emissions from Maine agriculture, as well as the cost that it might take to do so. The costs of each NCS practice were based on a mix of yield and revenue changes, capital expenditures, operating costs, and land rental rates. Periodic costs such as capital equipment or land acquisition were annualized over the study period (20 years) using a discount rate of 5% so that they could be directly compared with annual costs. More details on the sources of these costs are provided in Appendix B.

2.3.6 Avoided Cropland Conversion

As with forestland area, Maine has consistently seen declines in cropland and grassland between 2001 and 2016, averaging 1,190-1,560 acres per annum (Freedgood et al., 2020; Lark et al., 2020). Most of this recent conversion has been to development, which has varying costs based on the size and location of the area converted (Table 6). Estimated costs for avoiding cropland conversion were derived from methods similar to Fargione et al. (2018). Future conversion was based on extrapolating historical trends forward following the two data sources listed above. Costs of mitigation included opportunity costs of land sale, based on values derived by Nolte (2020). The conversion of agricultural land to development over the 15-year period is relatively small, particularly if the area converted was intensively managed cropland or dairy pasture.[23] However, some of the mix of land conversion is estimated to come from grassland, which is assumed to sequester some carbon over time. As a result, some agricultural landowners could be compensated for not converting their grassland to development, while others would not receive any payments for GHG mitigation. To simplify the analysis, we estimate the annual cost of conserving agricultural land is equivalent to the mean county-level fair market value of the land (Table 6), which is equivalent to the opportunity cost of avoided development. Further, we assume that the average acre of avoided conversion does not mitigate any GHG emissions relative to its current use.

2.3.7 Sensitivity Analysis

The Maine agriculture NCS practice model is dependent on a range of assumptions that varied in our literature review. These include the impact of practices on crop yields, farm revenue, and implementation costs. As a result, we conducted a sensitivity analysis where we use low, medium (baseline/core), and high parameter values for each of these key input assumptions. This approach allowed us to assess the relative influence of each parameter on the key model estimates, namely total mitigation cost and break-even carbon price for each practice. Note that we opted to exclude

[23] N.B., as the most recent year of the analysis is 2016, and thus does not include potential pressures of development that may have emerged in Maine over the past 5 years, particularly as a result of the COVID-19 pandemic.

Table 6. Maine agricultural land conversion rates and fair market value estimates.

County	Agricultural Land Converted (ac/yr)		Land Fair Market Value ($/ac)		
	Freedgood et al. (2020)	*Lark et al. (2020)*	*Minimum*	*Mean*	*Maximum*
Washington	4	160	$259	$1,087	$102,905
Hancock	36	21	$111	$1,970	$389,056
Knox	13	30	$510	$11,484	$395,648
Kennebec	168	100	$558	$4,776	$269,780
Waldo	82	77	$487	$2,807	$190,748
Lincoln	16	21	$489	$6,786	$325,320
Sagadahoc	37	6	$1,275	$11,041	$306,089
Cumberland	78	38	$1,149	$17,815	$624,078
York	73	23	$1,595	$10,744	$588,089
Penobscot	63	208	$84	$835	$174,453
Somerset	281	83	$88	$730	$124,751
Oxford	25	23	$69	$1,466	$136,518
Aroostook	250	639	$141	$326	$30,669
Piscataquis	14	77	$98	$563	$24,404
Franklin	16	5	$107	$1,217	$43,573
Androscoggin	31	48	$615	$5,142	$116,507
Maine Total	**1,187**	**1,558**	**$477**	**$4,924**	**$240,162**

sensitivity of GHG mitigation factors from this analysis due to the wide variation in maximum and minimum estimates. Furthermore, we did not analyze the effect of climate change on crop yields and mitigation potential due to lack of data.

2.4 Scenario Analysis

2.4.1 Shared socio-economic pathways

Scenarios allow researchers and policy-makers to study the scope and impacts of climate change as well as the impacts of responding to it (Kriegler et al., 2014). The Shared Socioeconomic Pathways (SSPs) are five narratives that were developed for the IPCC by an international team of experts to examine broad trends that could shape future society by 2100 and include socioeconomic factors like population, economic growth, education, urbanization and the rate of technological development. The narratives set baseline societal drivers and allow researchers to examine barriers and opportunities for climate change mitigation and adaptation strategies (O'Neill et al., 2014; Ebi et al., 2014; O'Neill et al., 2017). For this study, we followed the general SSP framework and adapted it to develop specific land use sector pathways for the state of Maine.

The general construct of five SSPs are shown in Figure 10 and include:

- SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)
- SSP2: Middle of the Road (Medium challenges to mitigation and adaptation)
- SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation)
- SSP 4: Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation)
- SSP5: Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

Two additional important components of the SSP framework are projections of population and income in the geographical region of interest, as they can be highly correlated with the demand and consumption of various commodities. This study utilizes county-level projections from Wear and Prestemon (2019) to specify how income and population is assumed to grow over time for each of the SSPs (Figure 11). The projections highlight that population could change from 1.3 million to between 1.2 (SSP3) and 2.4 (SSP5) million by 2070, while per capita income could grow from $34,500 to between $65,900 (SSP3) and $98,300 over the same time frame.

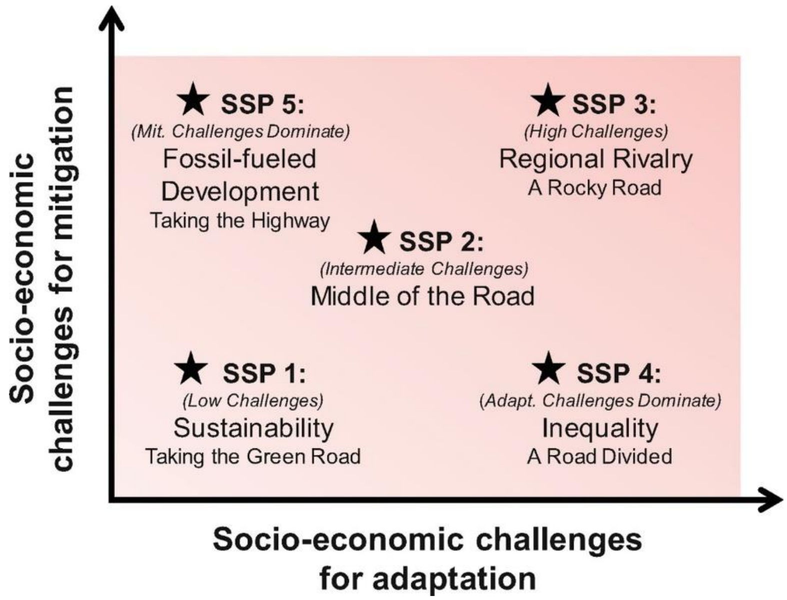


Figure 10. Five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and to adaptation. (Fig. 1 from O'Neill et al., 2017).

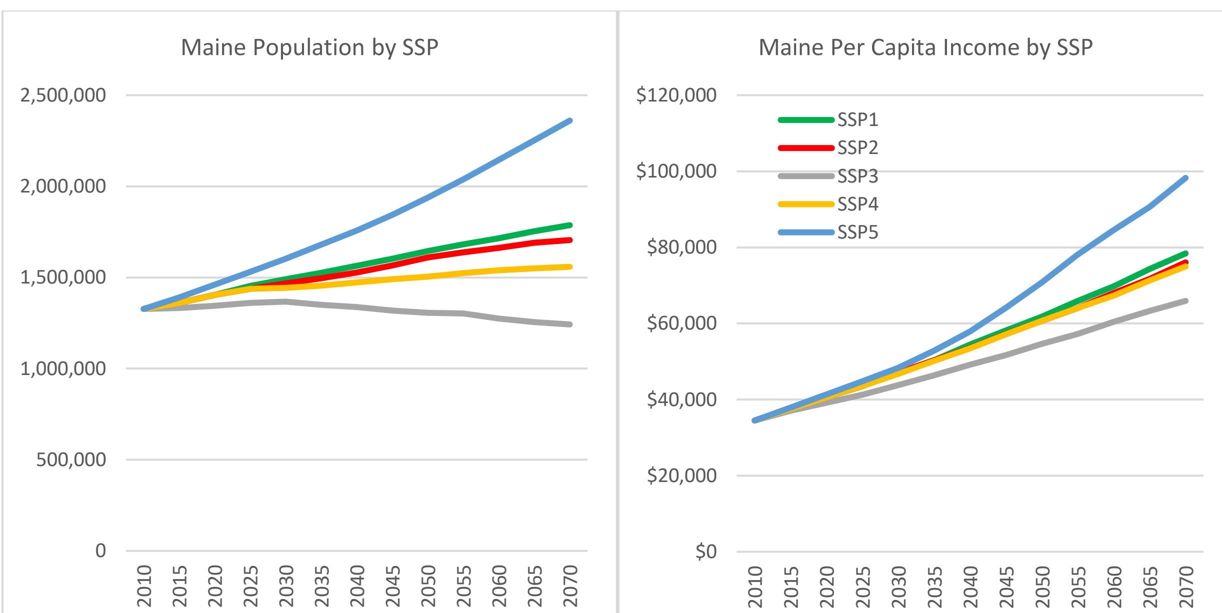


Figure 11. Maine population and per capita income by SSP, 2010-2070.

2.4.2. Scenario narratives for Maine's land use sectors

2.4.2.1 Maine Land Use Sector Pathways (LUSP) narratives

The following Maine land use sector pathways were developed to define possible future trends for working lands in Maine. A set of more detailed SSPs for Maine's land use sector, including agriculture and forestry, are needed because many national-level estimates are reliant on assumptions more applicable elsewhere and Maine foresters and farmers may face unique barriers and opportunities to mitigate and adapt to climate change. The Maine LUSP narratives described below were then parameterized based on a mix of expert and stakeholder input, which are presented in Section 0.

SSP1: Sustainability – Taking the Green Road

In this pathway, Maine strongly embraces the goals of the Maine Climate Council and successfully implements natural climate solutions to reduce emissions and bolster carbon sequestration across both forestry and agriculture. Strong statewide climate policies align with national-level mitigation policy. Investment is directed to making communities throughout the state more resilient and to diversify rural economics. Economic growth is high with rapid technological change and highly connected markets. Maine experiences medium population growth with a focus on low footprint housing to accommodate the growing population. Land becomes more productive because of both the implementation of best management practices and technological advances. Energy needs are primarily met through renewable sources, including biomass.

Additional land is conserved by both public and private entities, and few timber industry management organizations (TIMOs) exist. The forestry industry is focused on the production of sustainable, long-lasting products and the efficient use and distribution of biomass. Best management practices are mandatory, and the state has an increased implementation and enforcement capacity. The demand for (and harvest of) wood-based products and energy is relatively high because of the focus on renewable sources.

Because of a shift to less GHG-intensive diets, the acreage devoted to dairy farming decreases. The dairy farms that remain implement manure management best practices and capture methane for electricity needs. Emphasis on renewable energy and carbon sequestration increases the demand for forested land with an accompanying reduction in less profitable agricultural land. Technological advances and adoption of best management practices increase crop yields per acre and carbon sequestration. These advances also enable farmers to take advantage of longer growing seasons and increase their production per farm. Interest in healthier and more sustainable lifestyles expands organic farming practices with an accompanying reduction in fertilizer use and improved water quality. The desire for locally grown food leads to an increase in community farms and personal gardens. Maine's total agricultural land area decreases slightly, but there are overall increases in sector productivity and profitability with fewer bankruptcies and longer-term ownership of farmland. Some grasslands revert to natural forests as well. The commercial agricultural sector is dominated by diversified organic and/or sustainably managed farms as well as technologically advanced potato and blueberry farms.

SSP2: Middle of the Road

Social, technological, and economic trends continue to follow historical trends into the future. The state develops mitigation and adaptation plans under the Maine Climate Council; however, numerous social and technological obstacles and uncertainties prevent widespread implementation of successful strategies. A national climate change mitigation strategy is developed with modest ambition. Alternating state-level political administrations limit sustained climate change action. Energy needs are primarily met through renewable sources, including bioenergy from manure, continued use of fuelwood, hydro, and some wind and small solar installations.

Recent forest industry trends continue, and current regulations are still in place. Forest certification and best management programs are voluntary, but important, programs to maintain water quality and forest health. Demand reflects the historical mix of sawlogs, pulp, and fuelwood, and there is relatively low demand for biomass and other uses of small diameter timber.

Most commercial agricultural production continues to be marginally profitable, except for potatoes and blueberries. There are some gains in crop yields and reduced energy intensity in agricultural production, which has a positive effect on farm efficiency and sustainability. Some dairy farms, particularly in the southern part of the state, expand and partner with nearby farms to increase use of manure as a soil amendment. Dairy farms in central and southern Maine install digesters to capture the methane produced by cow manure. Some unprofitable agricultural land naturally reverts to forests, particularly grasslands. The overall number of farms across the state remains steady.

SSP3: Regional Rivalry

The state pursues a Maine-focused approach to economic development, but growth is relatively slow. Technological development is slow with little investment in sustainable solutions. Population growth is stagnant, thereby limiting investment and capacity in the land sector. No national climate change mitigation policy exists, and the work stemming from the Maine Climate Council ceases. Further, the demand for new construction is low as a function of few economic resources, and there is a focus on renovations when absolutely necessary.

The forestry industry has high demand for woody biomass for heating. The lack of building demand results in the production of mostly low-grade pulp and fuelwood. Forestry regulations are relaxed or eliminated. For example, the Forest Practices Act is eventually repealed. As a result, the number of clearcut harvests increase and few landowners are enrolled in forest certification programs.

An emphasis on Maine grown products expands agricultural lands, particularly in iconic Maine commodities like potatoes and blueberries. Dairy production expands at the expense of some forested land. Prioritization of Maine-based energy sources and increased energy demand expand the use of bioenergy. Relaxed pollution standards also enable the expansion of pastoral farming. Widespread environmental degradation and poor soil health decrease crop yields, making farming less profitable, particularly in Congressional District 2 (ME-02). Most farmers face a decline in farm income, leading to high turnover in land ownership. More frequent heavy precipitation events strain local resources and lack of state-level technological assistance increases the challenges for farmers. Congressional District 1

(ME-01) has modest technological investment and some crop yield gains; however, these gains make farming only moderately profitable in this part of the state. Exports of agricultural and forest products decrease to accommodate the demand for locally produced commodities, driven by this pathway's focus on a more region-based economy.

SSP4: Inequality

Stark socio-economic divisions deepen between ME-01 and ME-02. Strained internal divisions within the state hinder efforts for greater climate mitigation ambition state-wide. Although urbanization increases in southern Maine, a focus on sustainable planning limits urban sprawl. However, there is an increase of second homes located in rural areas in the North. ME-01 utilizes primarily renewable sources of energy, while ME-02 continues to be dependent on fossil fuels.

The forest industry in ME-01 is dominated by family-owned operations and conserved land. A mix of products are produced, and most landowners are enrolled in certification programs. ME-02 is still dominated by large landowners and TIMOs with production focused mostly on low-grade pulp and fuelwood with some sawtimber. Few family-owned operations exist in ME-02. Private interests dominate decision-making, and there is little enforcement of state regulations.

Farmers and forest landowners in ME-01 invests in natural climate solutions and sustainable farming practices, while also embracing rapid technological development. The Maine Climate Council develops effective recommendations for climate change mitigation, but successful implementation has variable success because of resource constraints and is primarily limited to well-resourced farms with high NGO support. The overall number of farms decreases and is dominated by larger, more technologically advanced farming systems. Smaller farming operations are typically unprofitable. Potato farms consolidate in Aroostook County and are controlled by a few wealthy owners. Crop yields and production are high on large, well-resourced farms, and low on small operations. Bioenergy from wood products and the capture of methane from dairy manure are dominant energy sources in ME-01, whereas ME-02 relies on fossil fuels. Blueberry farms expand due to technological innovation.

SSP5: Fossil-Fueled Development

Maine pursues an energy and resource-intensive development path. National- and state-level climate change policies exist, but technological investment is focused on adapting to extreme climate events, rather than mitigating overall emissions. Maine uses its abundant forested land to justify high emissions from other economic sectors. Population growth and regional migration to Maine increase demand for local resources and expand urbanization, particularly in the southern region of the state. Environmental pollution, including GHG emissions, is primarily controlled through technological advances.

Plantation forestry increases to supply the demand for wood products. Management intensity is high, enabled by technological advancements and driven by high demand for a variety of forestry products. Best management practices are widely implemented, and most forests produce certified products. The forestry sector is dominated by large landowners and TIMOs.

Increased access to global markets increases the demand for and export of Maine products, particularly potatoes, blueberries, and wood products. Rapid technological change increases agricultural yields, and many farmers are willing to invest in emerging NCS practices like biochar in addition to continuing to use fossil-based inputs as part of their production process. Farmers also focus on lengthening the growing season to increase production. Demand for meat expands pastoral land and stock numbers, but technological advancement in manure management allows most of the methane emissions to be captured and used as biogas.

2.5 Focus Groups

We used focus groups and surveys to determine opportunities and barriers farmers and foresters face, to inform development of the modeling framework, and to engage stakeholders to gauge the degree to which the NCS practices in Table 1 could be implemented. The stakeholders included small and large forest landowners, forest managers, and farmers with potato, blueberry, diversified vegetable, and dairy systems. The results of this stage will help us develop alternative scenarios to estimate uncertainty in NCS mitigation potential under a range of alternative climatic, policy, and socio-economic futures (O'Neill et al., 2017).

Focus groups and surveys at large meetings of farmers began in the first quarter of 2020 but were interrupted by the outbreak of the COVID-19 pandemic. Additional focus groups were conducted in January-March 2021. The format of the focus groups was consistent with other methodologies from questionnaires and focus groups with U.S. farmers and foresters (Krueger & Casey, 2014; Rees, 2005) including the clear establishment of goals and rules for discussion (Doll *et al* 2017). The discussions in the focus groups were structured similarly to Hayden *et al* (2018) and Stuart *et al* (2014) to elucidate challenges and opportunities for farmers and foresters to implement NCS.

Potential participants were identified in consultation with stakeholder groups who are familiar with the range of enterprise and landowner types in Maine. Recruitment was conducted via mass email through the assistance of contact lists (i.e., listservs) managed by project collaborators, including the Maine Farmland Trust, UMaine Cooperative Forestry Research Unit, Maine Climate Table, Maine Woodland Owners, and the USDA Climate Hub. The volunteers participated in one of eight enterprise-specific (i.e., large forest landowner, potato farmer), facilitated focus groups consisting of four to 12 individuals. The volunteers filled out a short questionnaire immediately after the focus group discussion concluded. The 2020 in-person focus groups and questionnaire were 180 minutes, and the 2021 virtual focus groups and questionnaire were 120 minutes. A total of four forestry and four agricultural focus groups were conducted for this study.

3. Results and Discussion

3.1 Focus Group Feedback

3.1.1 Forestry

In early 2021, we conducted focus groups with large landowners, small landowners, and forest managers to understand barriers and opportunities for implementation of the NCS practices modeled in our interim report. The primary barriers to adoption included costs, administrative barriers (e.g., regulations, lack of information about or uncertainties in voluntary carbon markets, and/or time-intensive application processes), delayed return on investment from implementing practices, lack of labor, and concerns about the impact on the timber industry in Maine. Participants identified several opportunities to encourage adoption of NCS practices. Financial incentives, including offsetting implementation costs and diversifying revenue streams, were attractive to both small and large landowners with large landowners most likely to alter their practices. Although financial incentives are an opportunity for small landowner adoption, small landowners manage their forests for a variety of benefits in addition to economic return, limiting which practices they would consider adopting. Participants also expressed concern with mandatory climate markets but were supportive of well-regulated voluntary carbon markets. We used the data gathered from the focus groups to develop the scenarios presented in this report.

Key opportunities and barriers to adoption of forestry NCS highlighted by focus group participants are summarized in Table 7.

Table 7. Feedback of potential NCS opportunities and barriers from forestry focus groups.

Forest NCS Opportunities
Large landowners would implement pre-commercial thinning with financial incentive.
Both large and small landowners support ecological reserves for wildlife habitat, biodiversity, recreation, and a diversified landscape and would consider additional reserves with financial incentives.
Implementing NCS practices can help achieve other goals of foresters, such as improved stand health.
Landowners recognize wildlife habitat benefits as a potential additional incentive to implement longer rotations.
Removing upfront cost-share for smaller landowners would make NCS adoption more likely.
Extending rotations aligns with the goal of large landowners to increase timber stocks.
Pursuing NCS options aligns with many landowners’ sustainability values.
Forest NCS Barriers
Cost is a significant barrier for pre-commercial thinning.
Pre-commercial thinning is not cost-effective on small woodlots.
Clearcutting and monoculture plantations are not feasible on small woodlots.
Many owners of small woodlots manage their forests for aesthetic and wildlife habitat purposes; harvest revenue and carbon storage are not primary motivating factors.
There may be public opposition to clearcuts.
The banning of certain herbicides would prevent planting.
Information and administrative barriers involving USDA NRCS limit wider adoption of NCS practices.

3.1.2 Agriculture

We conducted focus groups with potato, lowbush blueberry, dairy, and diversified vegetable farmers to understand barriers and opportunities for implementation of the NCS practices modeled in our interim report. Barriers to adoption included labor, time, and management burdens including paperwork, upfront costs including equipment and materials, and questions about long-term ramifications. Opportunities to encourage adoption suggested by participants included direct financial assistance and market-based incentives, as well as technical support in meeting information needs and overcoming logistical challenges. Key opportunities and barriers to adoption of NCS highlighted by focus group participants are summarized in Table 8.

Table 8. Feedback of potential NCS opportunities and barriers from agricultural focus groups.

Agricultural NCS Opportunities
Providing transition payments to enable adoption of soil health building practices that can be costly to implement in early years but may result in long-term economic gains.
Creating market-based incentives by broadening markets for cover crops / rotation crops including forage crops and small grains.
Rewarding grower willingness to prioritize soil health by subsidizing practices that are already utilized and working well
Subsidizing production of biochar on farms or from locally produced feedstocks. Many growers expressed interest in substituting biochar for lime in applicable systems, given a similar price point.
Education and logistical support could facilitate adoption of digesters and SLS; smaller-scale on-farm investments to serve farm energy demands were of greater interest than larger commercial energy / cooperative models.
Agricultural NCS Barriers
Labor, time, management burdens / paperwork, and upfront costs were important constraints across systems and NCS practices.
Our short growing season constrains NCS practices including cover cropping due to limited time for field work operations and the desire to utilize growing degree-days for cash crop growth.
Constraints specific to organic farms include the additional costs of organic cover crop seed and the need for National Organic Program approval of amendments including biochar.
A key constraint on grower willingness to adopt biochar is the fact that there are many unknowns regarding biochar effects in Maine soils and growing conditions. Growers have expressed desire for long-term trials demonstrating safety and benefits for our region.
SLS technology and digesters are not compatible with all dairy bedding systems.
Increased use of manure as a soil amendment is desirable, but potential for increased adoption is low because available manure that is readily transportable is already being used.
Adoption of no-till and reduced-tillage operations on small farms can be constrained by lack of tools appropriate to the scale at which these farms operate.

Table 9. Summary of key SSP scenario elements

Element	SSP 1	SSP 2	SSP 3	SSP 4 – South ME	SSP 4 – North ME	SSP 5
Land productivity growth (annual %)	For: 0.75% Ag: 1.7%	For: 0.5% Ag: 1.2%	For: -0.25% Ag: -0.25%	For: 0.6% Ag: 1.5%	Lg For: 0.5% Sm For: 0.25%, Lg Farm: 1.2% Sm Farm: 0.5%	For: 1% Ag: 2%
Agricultural land use mix (% baseline area)	Crop loss: 10% Hay: 39% Potato: 10% Berries: 9% Grains: 25% Veg: 5% Apples: 2%	Crop loss: 5% Hay: 45% Potato: 14% Berries: 11% Grains: 20% Veg: 3% Apples: 2%	Crop loss: -5% Hay: 49% Potato:12% Berries: 10% Grains: 20% Veg: 2% Apples: 2%	Crop loss: 5% Hay: 72% Potato: 0% Berries: 6% Grains: 1% Veg: 10% Apples: 6%	Crop loss: 0% Hay: 40% Potato: 18% Berries: 14% Grains: 25% Veg: 2% Apples: 1%	Crop loss: 5% Hay: 42% Potato: 14% Berries: 14% Grains: 20% Veg: 3% Apples: 2%
Dairy stock numbers (% baseline stock)	Dairy: 80%	Dairy: 100%	Dairy: 120%	Dairy: 80%	Dairy: 110%	Dairy: 130%

The model approach presented in our interim report was refined through feedback from these focus groups and through semi-structured interviews conducted with Cooperative Extension personnel. Mulch was added as a relevant NCS practice in lowbush blueberry and diversified vegetable systems. Our assumed potato rotation was changed to a 2:1 rather than a 1:1 rotation crop to cash crop system in order to reflect recent trends in grower practices. Potential rates of biochar adoption,[24] mulch adoption,[25] and conversion to perennial set-asides[26] were adjusted to less than theoretical maxima of 100% adoption in order to better reflect practically achievable maxima. Data gathered from these focus groups and interviews were also used to inform the scenarios presented in this report.

3.2 Shared Socioeconomic Pathway Scenarios

We used feedback from the focus groups to make assumptions about socio-economic drivers of land use for the five SSPs. Table 9 provides a summary of the key elements used in our scenario analyses. Table 10 depicts the assumed rate of adoption of the NCS practices.

3.3 Forestry

3.3.1 Model Baseline

Circa 2010, LANDIS-II estimates based on initial forest conditions indicated there was approximately 133 million metric tons of aboveground carbon (MMTC) distributed broadly across our 9.1 million acre study

[24] Maximum biochar adoption rates were set to 50% for hay and haylage, 90% for diversified vegetables, and 75% for all other applicable systems.

[25] Maximum mulch adoption rates were set to 100% for lowbush blueberry and diversified vegetables.

[26] Maximum set-aside adoption was set to 15% of acreage in applicable systems.

Table 10. Assumed distribution of NCS practice adoption area by SSP (% total area).

NCS Practice	SSP 1	SSP 2	SSP 3	SSP 4 – South ME	SSP 4 – North ME	SSP 5
Agricultural Crops						
Base practice (no mitigation)	0	75	75	0	100	0
Cover crops	10	0	25	15	0	15
Reduced till	15	0	0	15	0	20
Biochar	0	25	0	0	0	0
Conversion to perennials	15	0	0	10	0	0
Riparian buffers	10	0	0	10	0	0
Biochar + cover crops	50	0	0	50	0	65
Dairy						
Base (no mitigation)	0	50	100	0	100	0
Large Complete Mix AD with elec. gen.	25	20	0	25	0	25
Solid-liquid separation (SLS)	25	20	0	25	0	25
Small Complete Mix AD with elec. Gen.	25	5	0	25	0	25
Plug Flow AD with elec. gen.	25	5	0	25	0	25
Forestry						
Base (90% partial / 10% clearcut)	0	50	50	30	30	0
Extended rotation (Min 100 years)	25	0	0	0	0	0
35% clearcut	0	0	25	0	0	0
50% clearcut + plant	0	0	25	50	50	75
35% CC & plant + 20% Set Aside	75	50	0	20	20	25

Notes: blue = medium timber harvest intensity; green = high timber harvest intensity

area (Figure 12). At the cell-level, which represents approximately 0.1 ha or 0.22 ac, aboveground carbon averaged 4,250 g m^{-2} (range = 116-7,976 g m^{-2}). Under the baseline scenario (i.e., BAU min50 under RCP 2.6 and median harvest level), total aboveground carbon was projected to remain relatively stable (133 MMTC +/- 4% of total C), with a notable increase in the last period coinciding with a drop in harvest level (Figure 13). On average, 26.7 MMTC of aboveground carbon was projected to be harvested (i.e,. removed) every 10 years, with a trend of declining supply after 2060. The total harvest footprint every 10 years was projected to be 1,440,000 acres on average, which translated into an annual harvest rate of approximately 1.9% projected for the study area 2010-2100. Under the increased/decreased demand scenarios, total aboveground carbon followed the same trend over time as BAU min50 (+/- 15%) with the greatest impact to supply occurring in the short term (i.e., 2020-2040).

Harvest levels in the 9.1 million acres of northern Maine tracked in the LANDIS model were estimated to be maintained around 9.3 million green tons per year, which is consistent with trends over the past 10 years. These harvests were expected to be a similar mix of sawlogs, pulpwood, and low-diameter biomass that were converted into forest products, again matching historical trends. As a result, the BAU harvest of about 145,000 acres each year—of which 90% was partial harvest—was estimated to accrue $120 million per year in stumpage revenue. These estimates were the values against which all the other LANDIS-based scenarios were compared in this study.

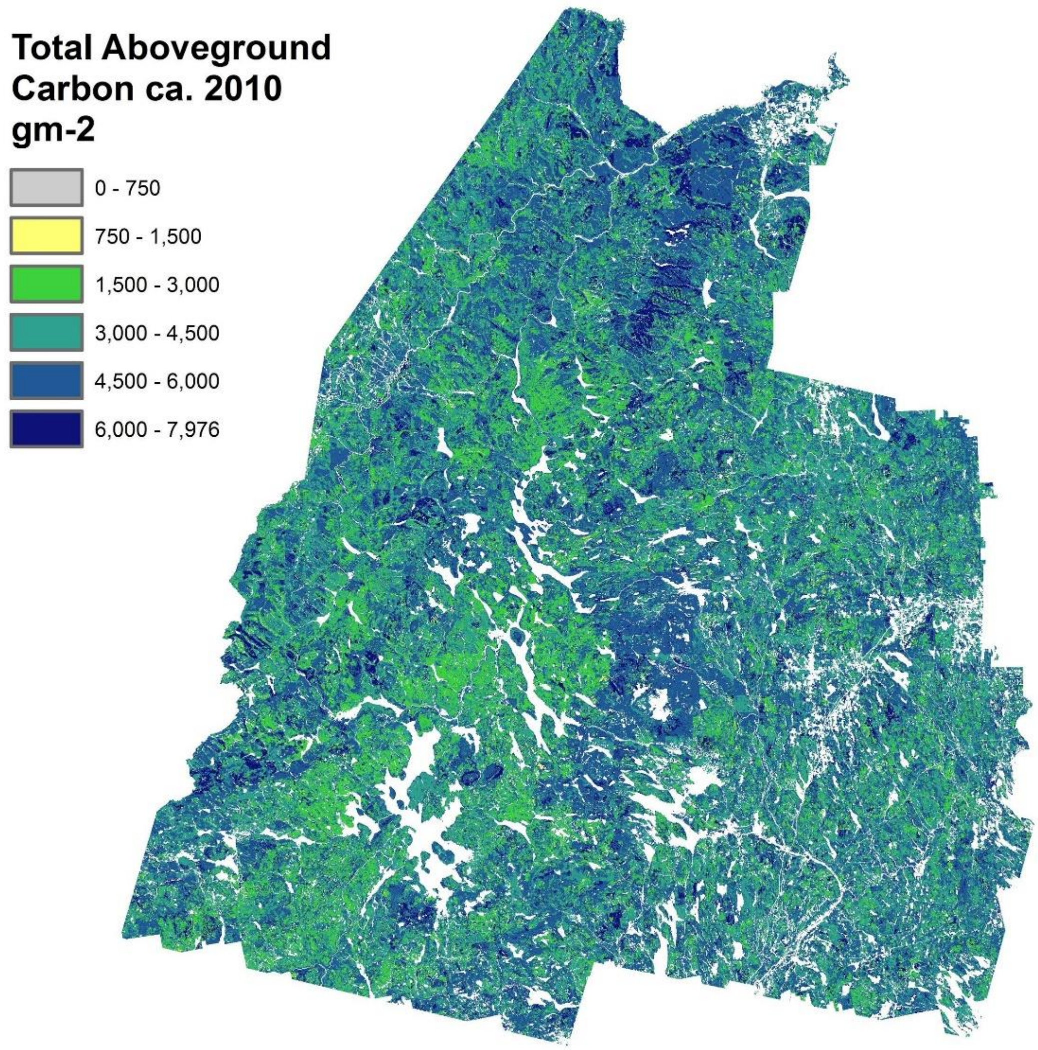


Figure 12. Spatial distribution of total aboveground carbon ca. 2010, also representing the starting conditions for forest landscape simulations 2010-2100.

Forest NCS Practice Results

3.3.1.1 Forest management in LANDIS

Total aboveground carbon followed a variety of future trends, including increasing and decreasing, under RCP 2.6 and five of the NCS scenarios modeled with LANDIS-II (Figure 13). Aboveground carbon was most variable under the Extended Rotation scenario (Min100). Carbon first increased from 2010 to 2040 as a result of decreased harvesting activity due to a lack of stands yet eligible for harvest (i.e., at least 100 years old), decreased from 2040 to 2080 as stand aging allowed harvesting activity to increase, and then increased again from 2080 to 2100 as the number of eligible stands was reduced. In contrast, aboveground carbon followed an increasing trend and supply was less variable under the other NCS scenarios. All the NCS scenarios resulted in a higher net increase in aboveground carbon from 2010 to 2100, ranging from 12-61% compared to the BAU min50 scenario (3%). Increased intensive management (e.g., clearcut harvesting followed by planting) resulted in increased stocking and growth, which contributed to the system-wide increase in aboveground carbon. However, much of the increase was also a result of the reduction in the total harvest footprint, which allowed more of the pool of standing carbon to remain on the stump and continue to sequester carbon. This pattern was clearly evident in the increased set-asides scenario (Set20).

Converting the aboveground and harvested carbon into annual figures allows us to estimate the annual change in carbon sequestration over different time periods as well as the cost of implementing a specific NCS practice compared to the BAU (typically in the form of lost revenues or increased planting and management costs). Figure 14 indicates that extending the minimum stand age before harvest out to 100 years increased forest carbon over the first 20 years because many stands that were harvested under BAU were instead left to mature. However, those increases in carbon diminished over time as the same stands were then harvested between 2040 and 2070. In contrast, stands that involved active planting and/or set-asides continued to sequester carbon on a steady basis over the next 50 years. We estimated that simply clearcutting stands but not artificially regenerating them produced minimal carbon gains above the BAU case.

Adjusting management to have longer rotations or to establish 20% of total forest area as no-harvest set-asides resulted in a noticeable reduction in timber harvests (13-17% below BAU) over the next 50 years (Figure 15). All other scenarios projected changes of 8% or less. This finding suggests that for many of the proposed forest management options, it is possible to increase forest (and harvested wood product) carbon while simultaneously maintaining a consistent timber supply that is close to historical levels. Furthermore, the ability to maintain timber harvests suggests that there could be minimal leakage of forest carbon loss to other parts of the globe from implementing forest NCS in Maine. Thus, most of the additional carbon sequestration over the next 50 years is expected to come from changes in the forest growing stock rather than harvested wood products (Figure 16).

The modeled scenarios indicate changes in total timber harvests and revenue coupled with increased costs associated with the planting scenarios that represent overall total costs for implementing these NCS relative to the BAU (Figure 17). The Min100 scenario accrued the most costs over the first 20 years due to high opportunity costs associated with reduced harvests. When the analysis was extended to 50 years, scenarios that involved planting faced the highest costs. However, those higher costs resulted in greater amounts of carbon being sequestered on the stump and greater numbers of harvested wood products, thereby reducing the break-even carbon price that a landowner may be willing to receive to implement a specific practice (Figure 18). When assessing the GHG mitigation cost from this perspective, it is clear that most forest management NCS practices can be implemented at a cost of \$10-20/tCO_2e, which is relatively inexpensive compared to most non-NCS opportunities.

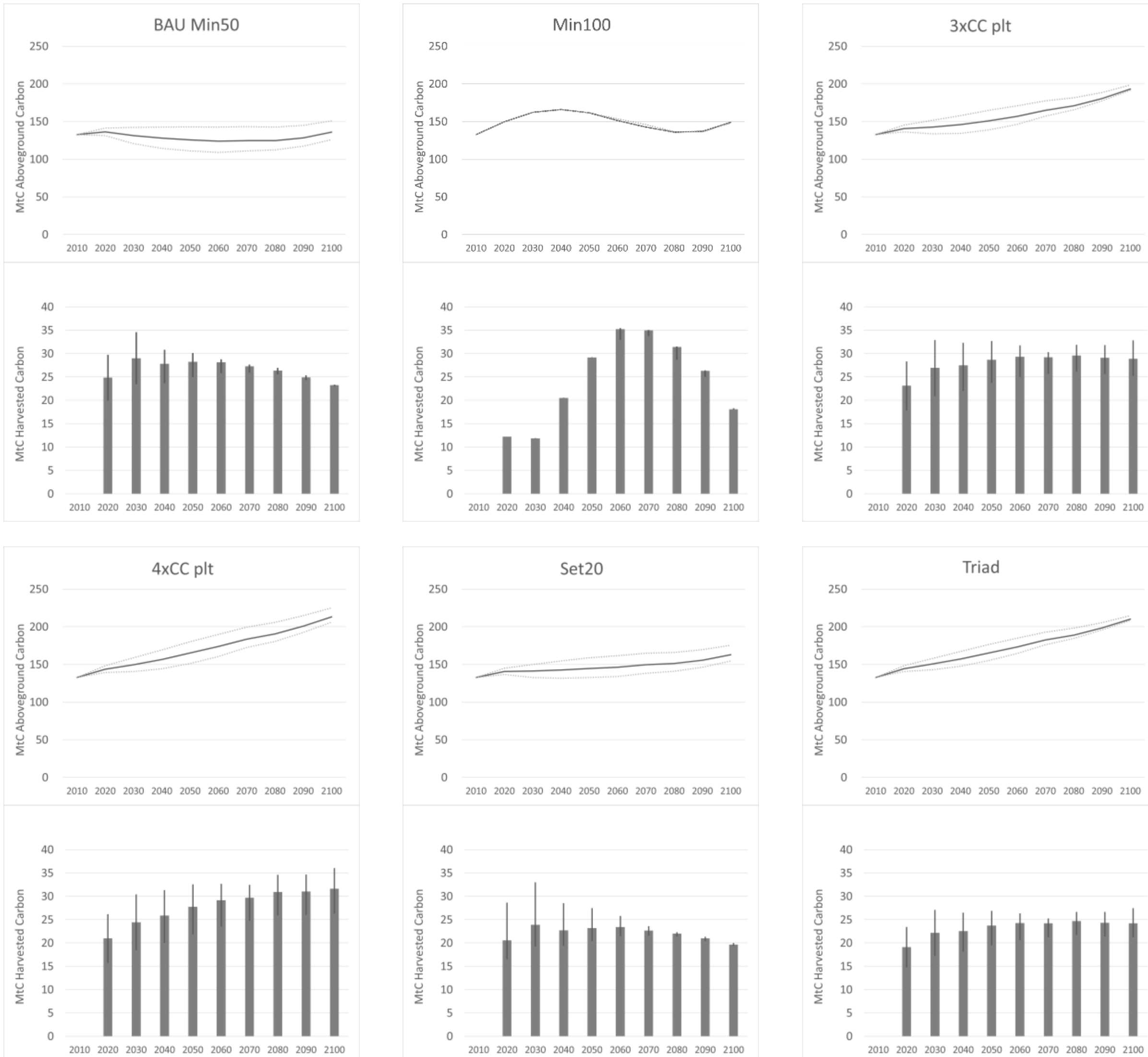


Figure 13. Dynamic estimates of aboveground and harvested carbon (MtC) for baseline and key NCS.

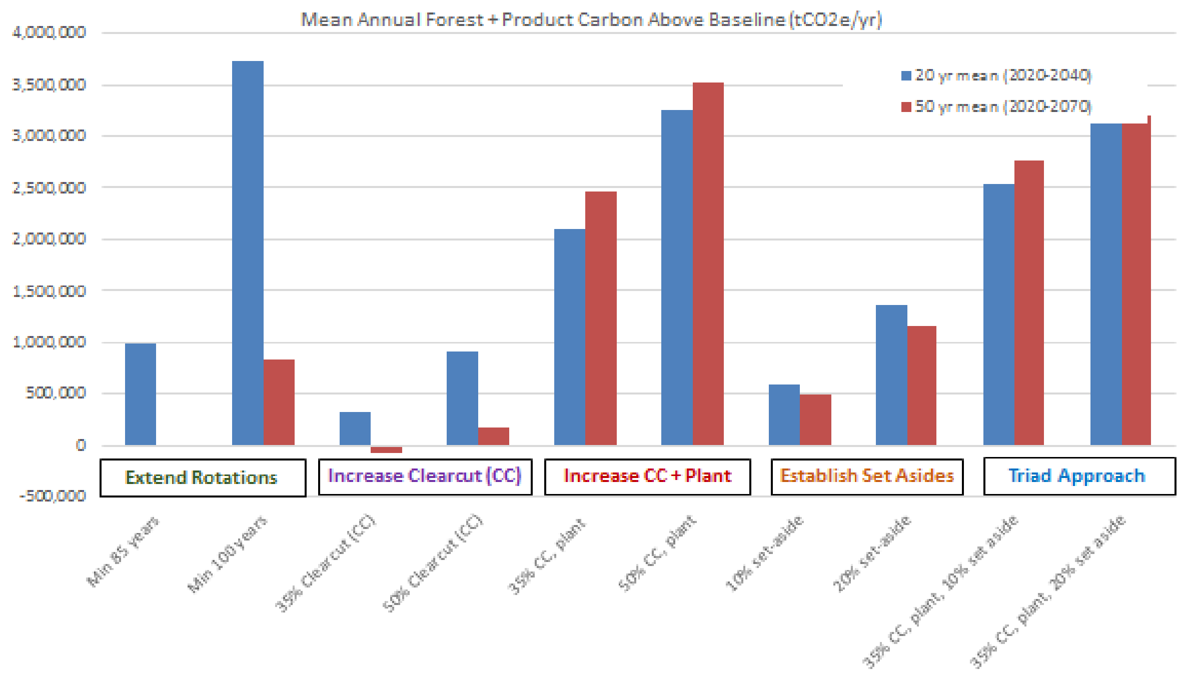


Figure 14. Mean annual forest and harvested wood product carbon change from BAU.

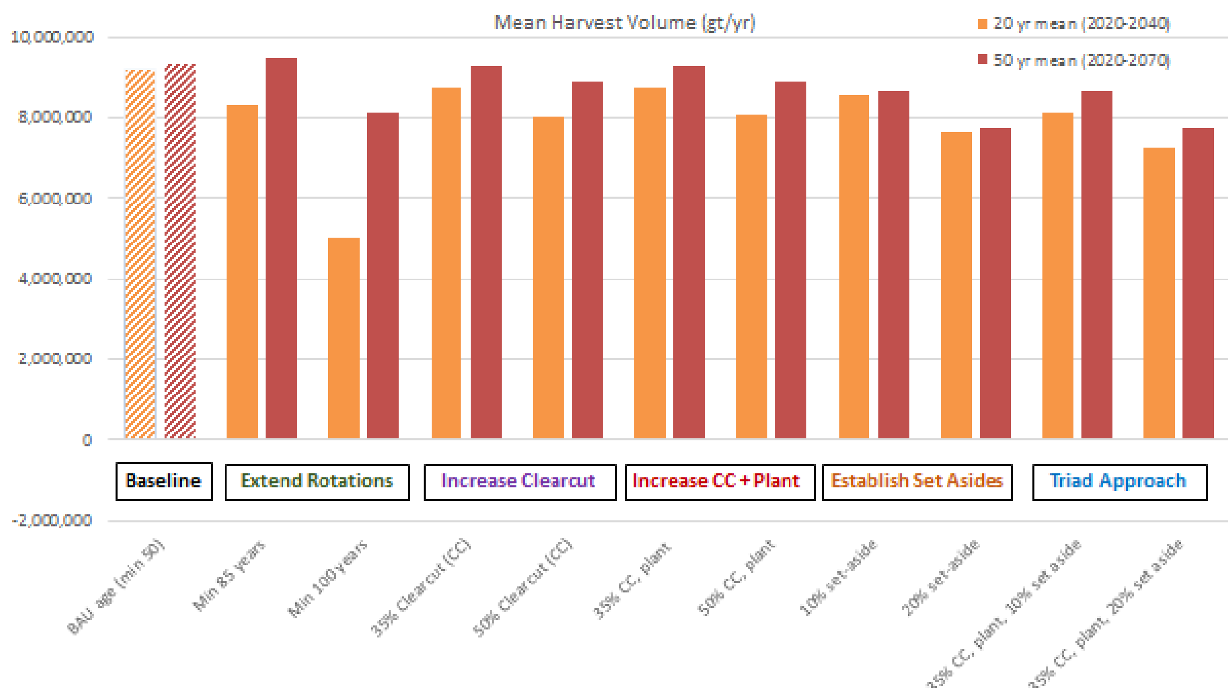


Figure 15. Mean annual timber harvest volume.

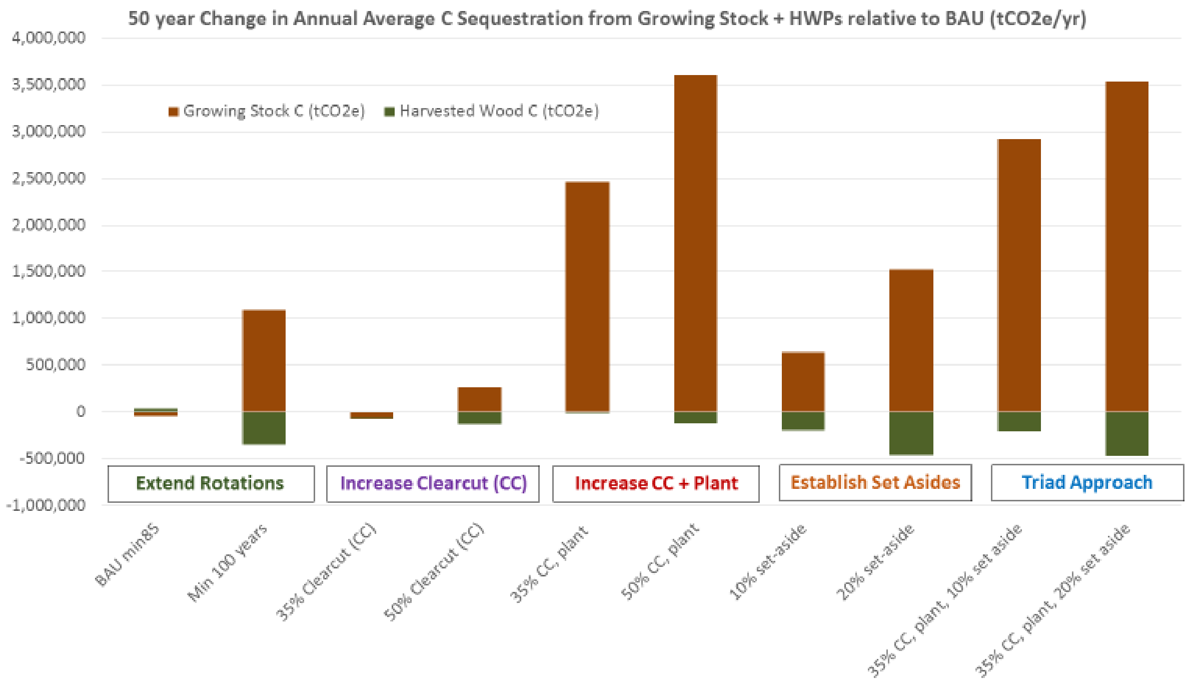


Figure 16. 50-year mean annual forest and harvested wood product carbon change from BAU, by pool.

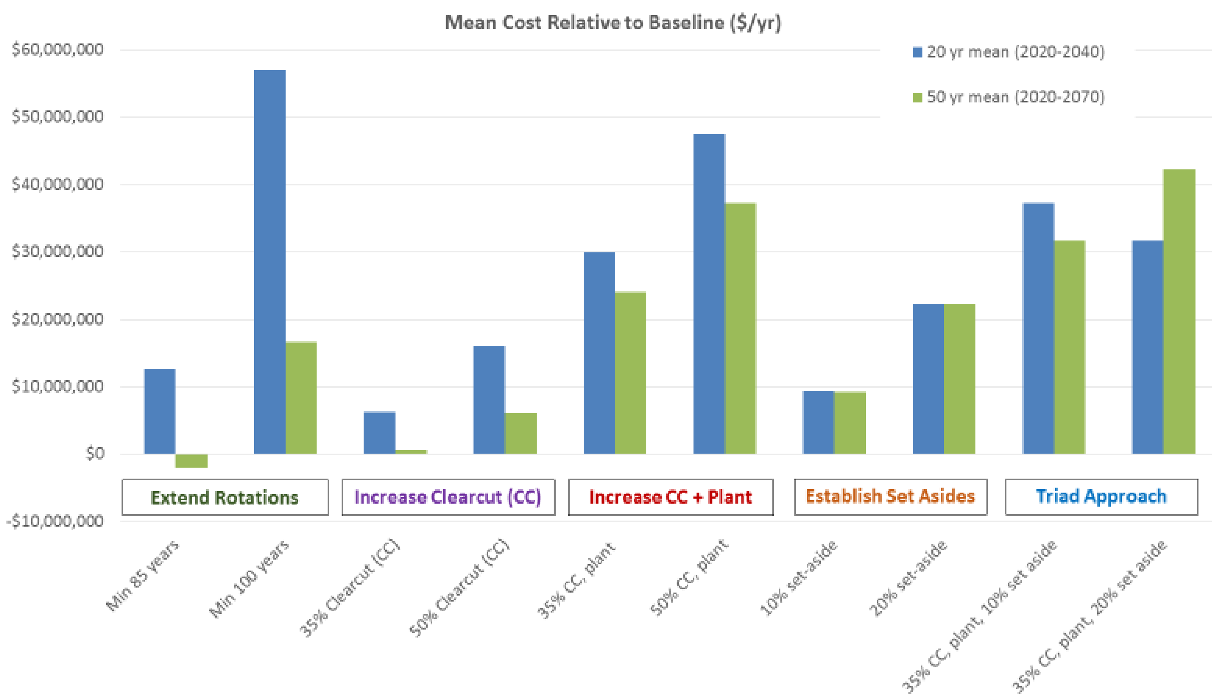


Figure 17. Mean total annual mitigation cost relative to BAU.

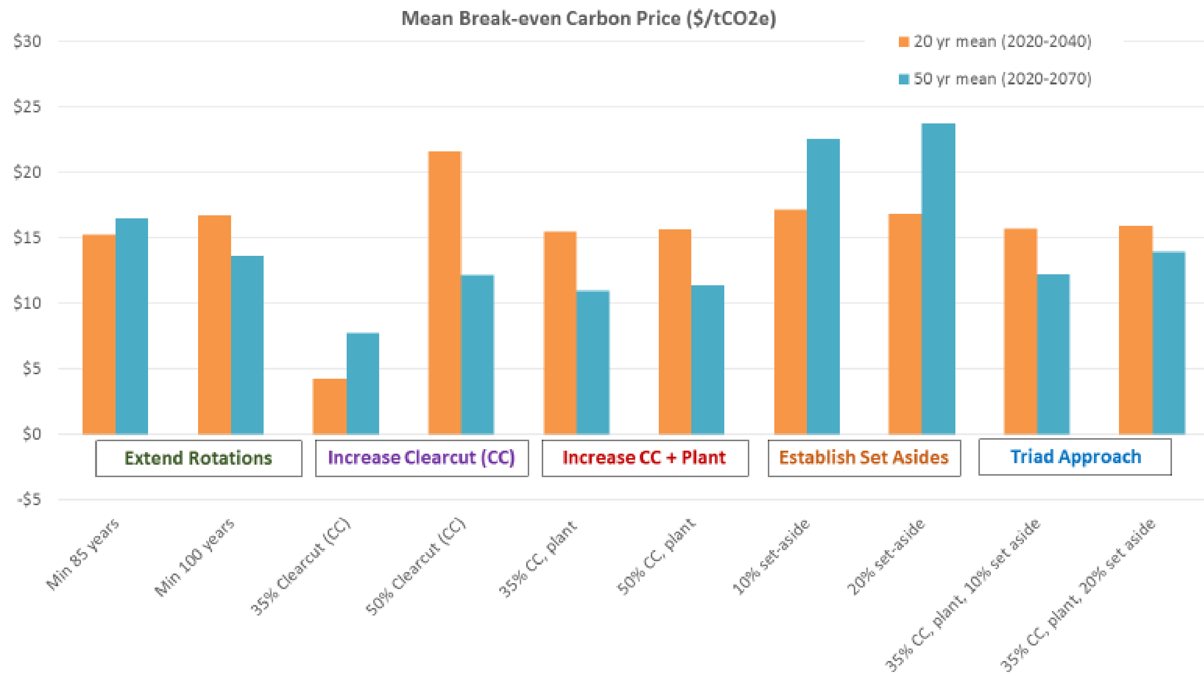


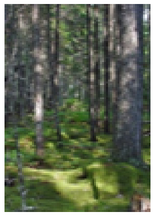
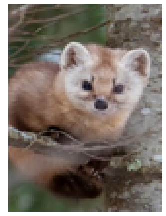
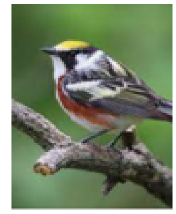
Figure 18. Mean break-even carbon price relative to BAU.

3.3.1.2 Impacts to biodiversity indicators

Under the baseline scenario (BAU min50 under RCP 2.6) and median harvest level, the extent of well-stocked mid-successional forest was projected to decline with the continuation of a harvesting regime dominated by partial harvesting. As a result, marten habitat (forest with basal area >80 ft^2/ac) was projected to decline (Table 11). Early-successional hardwood forest (and associated bird habitats) was projected to increase, a product of overstory removals promoting hardwood regeneration. In contrast, early-successional spruce-fir forest (and lynx foraging habitat) was projected to decline. Late-successional forests, both spruce-fir and northern hardwood, were projected to increase, largely a result of aging forest reserves.

Impacts to biodiversity indicators relative to our baseline varied across the NCS scenarios and revealed tradeoffs associated with forest developmental stage (Table 11). Late- and mid-successional forest conditions, including marten habitat, were generally projected to improve between 2010 and 2100 under the Extended Rotation scenario (Min100), or with increased set-asides (Set20 and Triad). Not surprisingly, the extent of lynx habitat increased with increased intensive management targeting spruce-fir forest regeneration (i.e., 3 times historical clearcut and planting (3xCC + plant), 4xCC + plant, and Triad). All NCS scenarios resulted in a reduction in early-successional bird habitat relative to the baseline.

Table 11. Summary of impacts to forest types and habitat for key forest NCS scenarios.

						
		LS SF	LS NH	Marten	Lynx	ES bird
BAU min50	2050	116%	118%	-34%	-60%	497%
	2100	72%	99%	-29%	-59%	331%
Min100	2050	0%	-3%	24%	-32%	-16%
	2100	27%	23%	13%	-6%	-16%
3xCC plt	2050	-10%	-5%	-7%	501%	-30%
	2100	-13%	-20%	-6%	545%	-39%
4xCC plt	2050	-13%	-3%	-7%	671%	-45%
	2100	-17%	-24%	-7%	715%	-50%
Set20	2050	25%	7%	17%	-26%	-18%
	2100	64%	18%	14%	-23%	-17%
Triad	2050	19%	2%	11%	395%	-43%
	2100	55%	0%	9%	432%	-49%

Notes: LS = late successional, ES = early successional, SF = spruce-fir, NH = northern hardwood. Colors signify the relative change from the BAU scenario, where green is an increase and orange a decrease.

3.3.1.3 Afforestation and avoided conversion

As discussed above, the afforestation and avoided forest conversion estimates were derived outside of the LANDIS model and encompass the entire state of Maine. Afforestation and restoration of areas that were determined to be forested historically, but not reduce agricultural production or require the conversion of developed land, was estimated to be feasible on about 360,000 acres of land across the state (Cook-Patton et al., 2020). The average afforested stand was estimated to sequester 2.1 tCO_2e/ac/yr, thereby yielding a total of 760,000 tCO_2e/yr in additional carbon sequestration. Implementing this NCS across Maine was estimated to cost about $22.8 million/yr, or $30/$tCO_2e$.. The average afforested stand was estimated to sequester 2.1 tCO_2e/ac/yr, thereby yielding a total of 760,000 tCO_2e/yr in additional carbon sequestration. Implementing this NCS across Maine was estimated to cost about $22.8 million/yr, or $30/$tCO_2e$.

Incentivizing forest landowners to avoid converting their land to other uses has a wide range of costs depending on the location of the threatened forest and what it is expected to be converted to. Following the historical trend that about 5,150 acres per year of Maine's forest is converted to agriculture or development, we estimated that this could be avoided at a cost of about $18.6 million/yr. Doing so would thereby result in an average of 1.1 $MtCO_2e$/yr of avoided GHG emissions from reduced forest loss per annum, at an average cost of $17/$tCO_2e$.

3.3.1.4 Summary of core modeled results

The 50-year average estimates of key results from all the forest NCS practices evaluated are summarized in Figure 19. The figure shows that many of the top mitigation options are expected to come from increasing clearcuts and planting and/or permanent set-asides. Afforesting marginal pasture and cropland could provide mitigation in addition to the improved forest management. We find that the average break-even carbon prices for most forest NCS practices range from $10-20/$tCO_2e$. Furthermore, if landowners could collectively change forest management across the 9.1 million acres in northern Maine from BAU to a 50% clearcut harvest regime followed by planting in addition to afforesting marginal land *and* reducing conversion of forests to agricultural and developed land across the state, we estimate that it could yield about 5.3 $MtCO_2e$/yr in additional carbon sequestration at a cost of $79 million/yr or $15/$tCO_2e$.

3.3.2 Sensitivity Analysis

3.3.2.1 Alternative climate change scenario sensitivity

Total forest carbon (live aboveground) was projected to be higher (1-2.5%) under the high emission climate scenario (RCP 8.5) across all management scenarios (Figure 20). Starting in 2050 there was a reversal in trends under RCP 8.5 that resulted in a negative net difference between RCP 8.5 and RCP 2.6. Total forest carbon was projected to be higher under the low climate emission scenario across all management scenarios between 2050 and 2100, and the carbon difference between RCP 8.5 and RCP 2.6 increased through time as temperatures continued to rise. Any positive effects of increased CO_2 on tree productivity were overwhelmed by productivity declines resulting from excessive heat limiting tree photosynthesis, particularly for northern conifers. Differences were greatest under scenarios with increased intensive management targeting spruce-fir forest regeneration, i.e., 3 and 4 times the current harvest area clearcut and planted (3xCC plt, 4xCC plt), which was a result of declines in productivity and regeneration success of spruce-fir species stemming from a combination of drought and excessive heat.

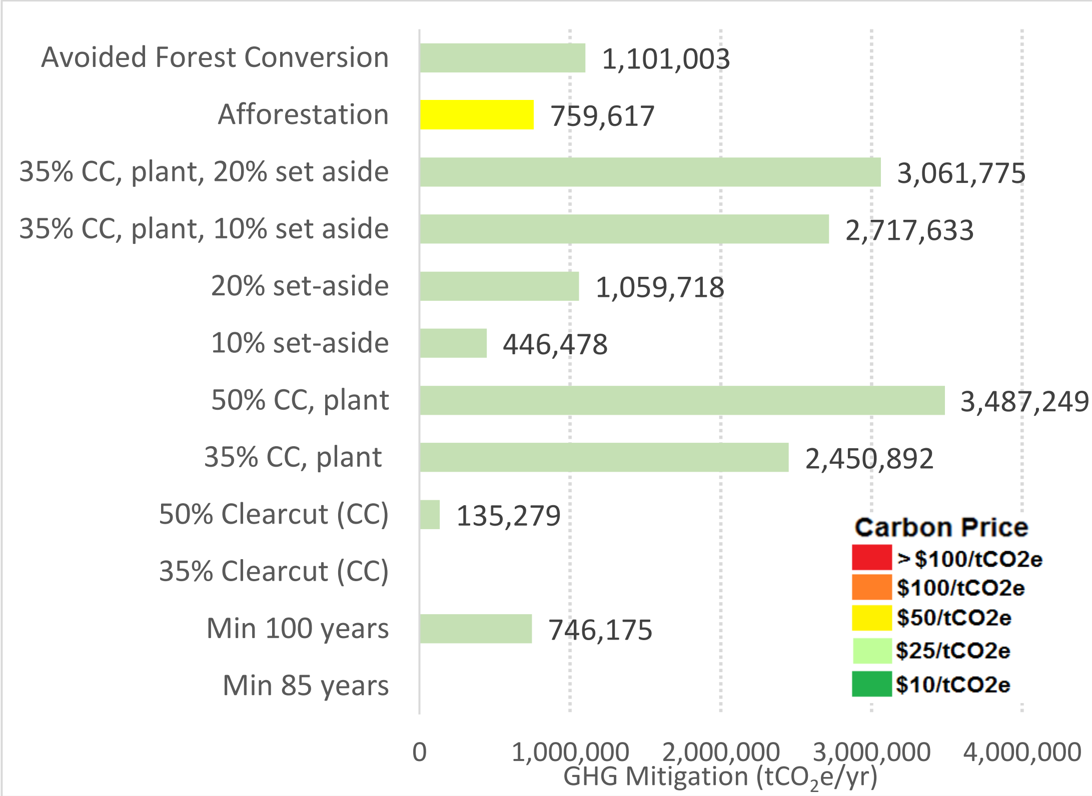


Figure 19. Total Maine forest NCS mitigation potential (tCO_2e/yr), 2020-2070 annual average, RCP 2.6. (Note: the avoided conversion and afforestation scenarios cover the entire state, while the other scenarios only include 9.1 million acres of managed forest in Northern Maine).

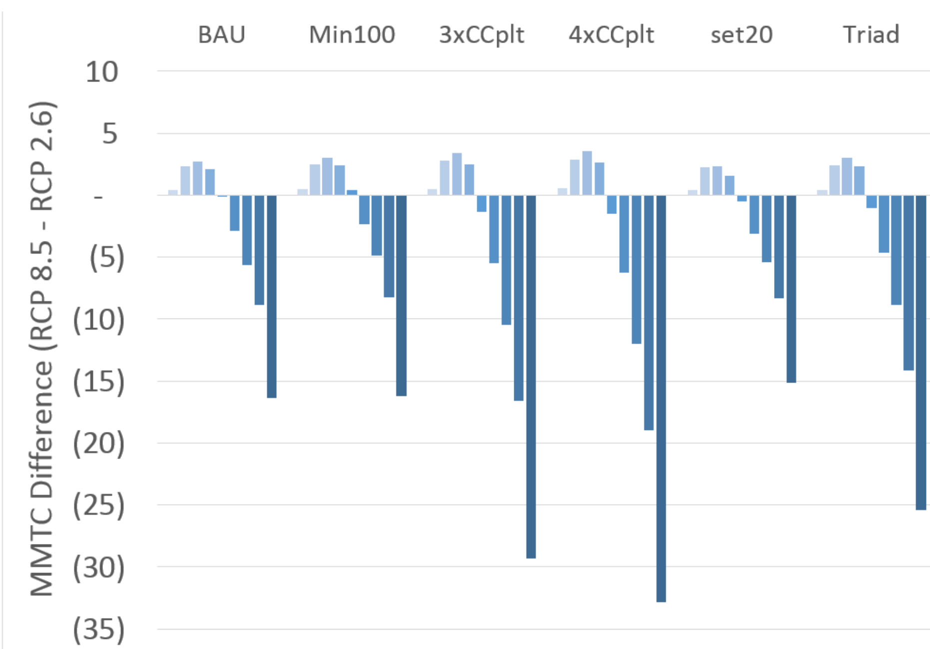


Figure 20. Difference in million metric tons carbon (MMTC) across scenarios for aboveground carbon per interval between RCP 8.5 and RCP 2.6. A positive difference indicates that total forest carbon stock was higher in each interval (e.g., 2010-2020)

Table 12 summarizes the key differences between RCP 2.6 and RCP 8.5 estimates based on a 50-year annual mean over 2020-2070. The analysis indicates that the most sensitive indicators are total forest carbon and total mitigation cost. Scenarios that specified more clearcuts and/or planting appear to be more sensitive to climate impacts, which makes sense as this approach accelerates forest succession. By design of our modeling exercise, mean harvest volume only differed by 1-2% between the two RCPs. It is important to note that these projections of future climate are based on modeled forest effects of changing temperatures and precipitation as well as the effects of increasing atmospheric CO_2.

Table 12. Key RCP 8.5 model estimates and differences from RCP 2.6 scenarios, 2020-2070 mean.

Scenario	Total Forest Carbon Above Baseline (tCO2e/yr)		Total Harvest (gt/yr)		Total Cost (mil $/yr)		Break-even carbon price ($/tCO2e)	
	RCP 8.5	*% Diff*	*RCP 8.5*	*% Diff*	*RCP 8.5*	*% Diff*	*RCP 8.5*	*% Diff*
Min 85 years	-3,516	-58%	9,836,856	1%	-$1.9	-3%	$16	-1%
Min 100 years	768,510	3%	8,414,053	1%	$17.0	2%	$14	0%
35% Clearcut (CC)	-69,497	-4%	9,646,008	1%	$0.6	13%	$5	-36%
50% Clearcut (CC)	139,862	3%	9,233,165	1%	$6.1	1%	$12	0%
35% CC, plant	2,290,221	-7%	9,653,847	1%	$24.2	0%	$11	3%
50% CC, plant	3,287,652	-6%	9,253,963	1%	$37.4	0%	$12	3%
10% set aside	454,183	2%	8,986,305	1%	$9.4	2%	$22	-1%
20% set aside	1,056,738	0%	8,041,245	2%	$22.0	-2%	$23	-5%
35% CC, plant, 10% set aside	2,582,127	-5%	8,957,788	1%	$31.9	1%	$13	3%
35% CC, plant, 20% set aside	2,960,420	-3%	8,009,964	2%	$42.1	0%	$14	3%
Afforestation	759,617	0%	9,694,027	1%	$22.8	0%	$30	0%
Avoided Forest Conversion	1,101,003	0%	9,694,027	1%	$18.6	0%	$17	0%

3.3.2.2 Economic benefits and costs sensitivity

The revenue and costs associated with timber harvests and planting can vary over time and space. As a result, we conducted a sensitivity analysis that adjusted the stumpage price and planting costs that landowners may face under different stand and market conditions by a factor of ±25% compared to our core assumptions. As expected, changing stumpage prices had a linear effect on total cost and break-even carbon prices for all scenarios that did not involve planting (Table 13). Low/high stumpage prices had a relatively lower impact on costs for scenarios that also included planting. This is because planting trees contributes to a relatively large part of the total cost incurred by forests undergoing that practice. This finding is confirmed with the planting cost sensitivity analysis, which estimated that adjusting planting costs by 25% could lead to a 12 to 25% change in total costs in implementing those management practices.

Table 13. Change in forest NCS mitigation costs for stumpage price and planting sensitivity analysis.

Scenario	Total Cost (Mil $/yr)				Break-even carbon price ($/tCO₂e)			
	Low Planting	*High Planting*	*Low Stumpage*	*High Stumpage*	*Low Planting*	*High Planting*	*Low Stumpage*	*High Stumpage*
Min 85 years	0%	0%	-25%	25%	0%	0%	-25%	25%
Min 100 years	0%	0%	-25%	25%	0%	0%	-25%	25%
35% Clearcut (CC)	0%	0%	-25%	25%	0%	0%	-25%	25%
50% Clearcut (CC)	0%	0%	-25%	25%	0%	0%	-25%	25%
35% CC, plant	-25%	25%	0%	0%	-23%	23%	-2%	2%
50% CC, plant	-21%	21%	-4%	4%	-21%	21%	-4%	4%
10% set-aside	0%	0%	-25%	25%	0%	0%	-25%	25%
20% set-aside	0%	0%	-25%	25%	0%	0%	-25%	25%
35% CC, plant, 10% set aside	-18%	18%	-7%	7%	-17%	17%	-8%	8%
35% CC, plant, 20% set aside	-12%	12%	-13%	13%	-12%	12%	-13%	13%
Afforestation	-33%	33%	-33%	33%	-33%	33%	-33%	33%
Avoided Conversion	0%	0%	0%	0%	0%	0%	0%	0%

3.3.2.3 Harvest intensity sensitivity

Another potential key driver of forest carbon sequestration can be the annual level of timber harvested. To test this effect on the study area, we modeled the effect of adjusting annual harvests by +/- 20% (i.e., high and low demand) compared to historical (base) demand for five of the NCS scenarios that were found to have some of the largest forest carbon changes under our core assumptions (Figure 21). Estimates indicate that lower harvest levels can lead to relatively higher net forest carbon sequestration over the next 50 years, yielding 0.1 to 0.8 million tCO_2/yr more C on net than if harvests were about 20% below baseline levels. However, increasing harvests by 20% over the baseline does not necessarily result in overall reductions in forest carbon if key NCS practices are also implemented. Specifically, we find that a high timber demand scenario can yield between 0.5 and 2.8 tCO_2e/yr more than the BAU case, with the greatest increases occurring when there is a high level of planting after harvest.

As with the base demand scenarios, there are still costs incurred when implementing NCS practices, even in the case where harvest is assumed to increase over BAU (Figure 22). For the low demand case, lost revenues associated with implementing NCS practices could increase by $2-23 million/yr compared to base demand, with the largest cost increases associated with the more intensive clearcut and plant scenarios. Increasing demand for timber does increase overall revenue relative to BAU for the two clearcut and plant scenarios, however the relatively high cost of planting results in a net cost of $10 to $23 million/yr compared to the base BAU scenario.

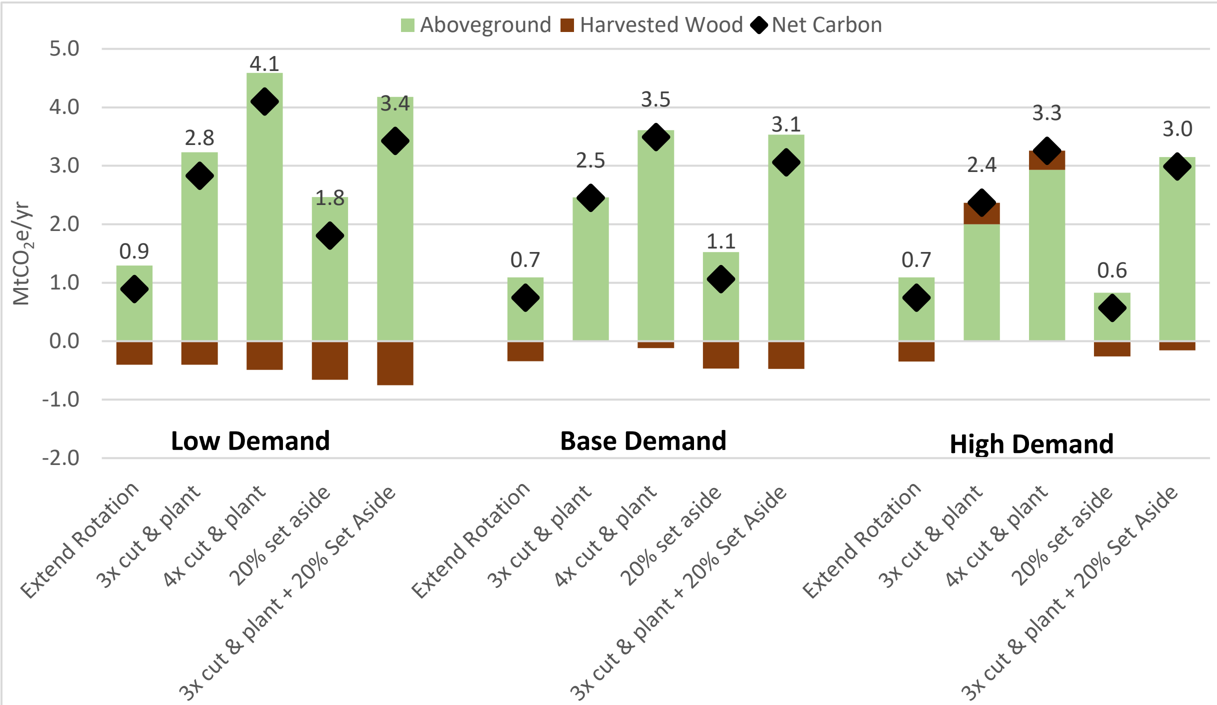


Figure 21. Change in mean annual forest carbon sequestration ($MtCO_2e$) relative to base BAU by carbon pool under alternative harvest demand scenarios.

Table 14. Estimated changes in key indicators relative to base BAU for alternative harvest demand scenarios.

Metric	Harvest Demand Scenario	Extend Rotation (Min 100)	3 x clearcut & plant	4 x clearcut & plant	20% set aside	3x clearcut & plant + 20% set aside
Aboveground C ($MtCO_2e/yr$)	Low	2.193	3.415	4.792	2.801	4.476
	Med	2.038	2.335	3.560	1.616	3.556
	High	2.025	1.512	2.562	0.743	2.882
Harvested Wood Product C ($MtCO_2e/yr$)	Low	-0.401	-0.488	-0.662	-0.753	-0.869
	Med	-0.345	-0.009	-0.121	-0.467	-0.473
	High	-0.346	0.369	0.328	-0.258	-0.159
Total C ($MtCO_2e/yr$)	Low	0.893	2.745	3.927	1.713	3.309
	Med	0.745	2.451	3.491	1.060	3.062
	High	0.744	2.368	3.258	0.569	2.991
Harvest (Mgt/yr)	Low	-1.444	-1.755	-2.381	-2.708	-3.125
	Med	-1.241	-0.033	-0.434	-1.679	-1.701
	High	-1.245	1.327	1.180	-0.929	-0.571
Revenue (mil $/yr)	Low	-$19	-$23	-$32	-$36	-$42
	Med	-$16	$0	-$6	-$22	-$23
	High	-$17	$18	$16	-$12	-$8
Planting Cost (mil $/yr)	Low	$0	$16	$24	$0	$13
	Med	$0	$24	$32	$0	$20
	High	$0	$32	$39	$0	$26
Total Cost (mil $/yr)	Low	$19	$39	$55	$36	$55
	Med	$16	$24	$37	$22	$42
	High	$17	$14	$24	$12	$34
Break-even Carbon Price ($/$tCO_2e$)	Low	$21	$14	$14	$21	$16
	Med	$22	$10	$11	$21	$14
	High	$22	$6	$7	$22	$11

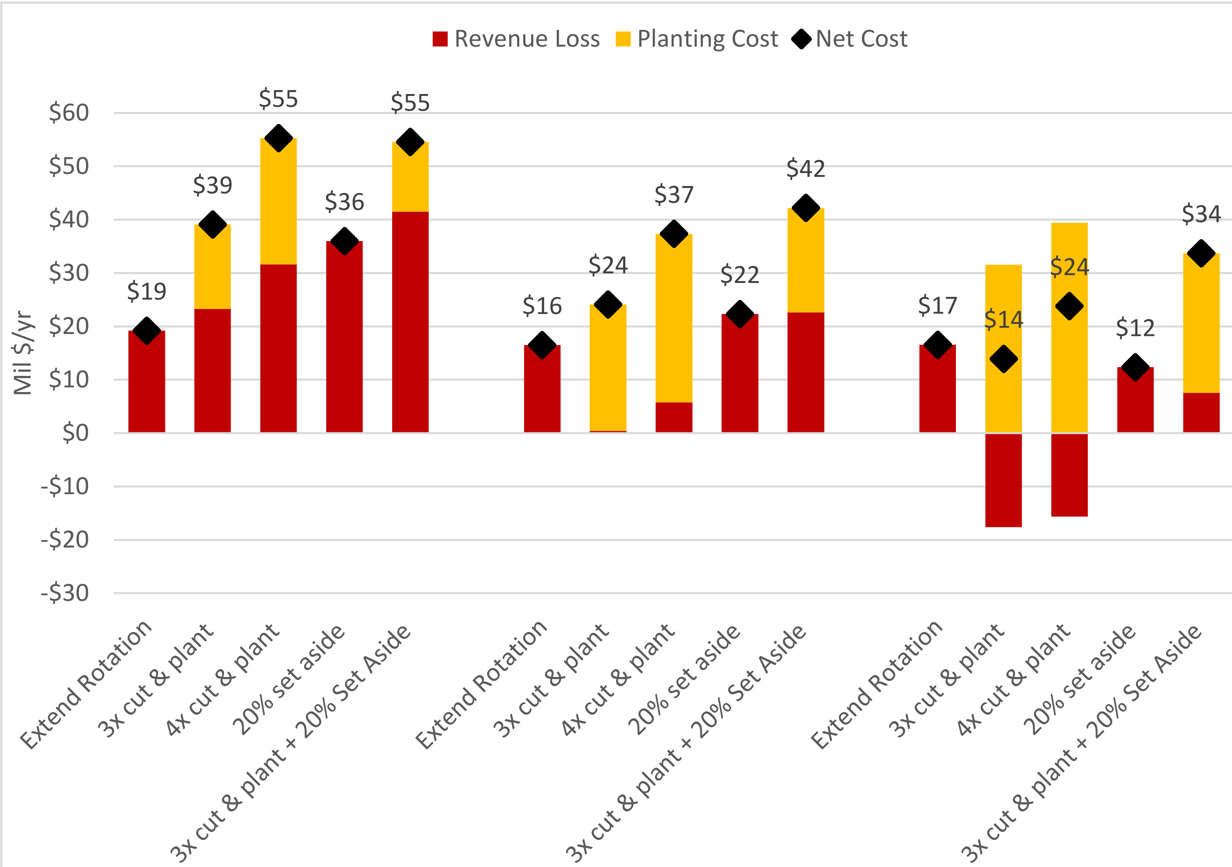


Figure 22. Change in mean annual stumpage revenue, planting, and total net costs (mil $/yr) relative to base BAU under alternative harvest demand scenarios.

Changes in annual harvest demand have a relatively minimal impact on the magnitude and ranking of mitigation costs on a $/t$CO_2$e basis (**Table 14**). In all cases, implementing NCS practices costs less than $25/t$CO_2$e, with set asides and extended rotations incurring the highest costs for all three demand scenarios due to lost revenues associated with removing land eligible for timber harvest but not accruing carbon at a fast enough rate to offset these losses. In contrast, the scenarios with planting are estimated to be the cheapest option for mitigation, on average, costing $6-14/t$CO_2$e.

3.3.3 Forest Shared Socioeconomic Pathways

For the SSP scenarios, we assumed the adoption level for each of the potential NCS practices (Table 10). The average break-even price ranges $8-15/t$CO_2$e (Figure 23a-c). The pathways that rely more heavily on clearcutting and planting without set asides have lower overall costs (SSPs 3-5), nonetheless the total GHG mitigation cost only ranges from $11-33 mil/yr across the five SSPs. SSP3 has the lowest total cost, but also significantly less GHG mitigation than the other SSPs. Total forest mitigation ranges 0.8-3.3 MtCO_2e/yr. In 2017, net GHG emissions in Maine were approximately 5 MtCO2e/yr, which means if Maine follows a pathway similar to SSPs 1, 4, or 5, then the forestry sector could contribute nearly half or more of the mitigation needed to reach the state's net zero goal at a cost of $21-33 mil/yr, absent of any changes in GHG emissions from the transportation and other energy sectors.

Harvest levels in Northern Maine could fluctuate by as much as +/- 8% across the five pathways relative to the baseline of 9.5 million green tons per annum. A focus on implementing more set-asides in SSP1 and SSP2 could reduce harvests by about 0.8 mil gt/yr, while increasing clearcutting and planting coupled with a higher harvest intensity in SSP5 could increase harvests by 0.7 mil gt/yr. Harvests are estimated to be relatively comparable to historical levels for both SSPs 3 and 4.

More detailed results of the Maine forest sector SSPs are listed in Table 22 of Appendix A.

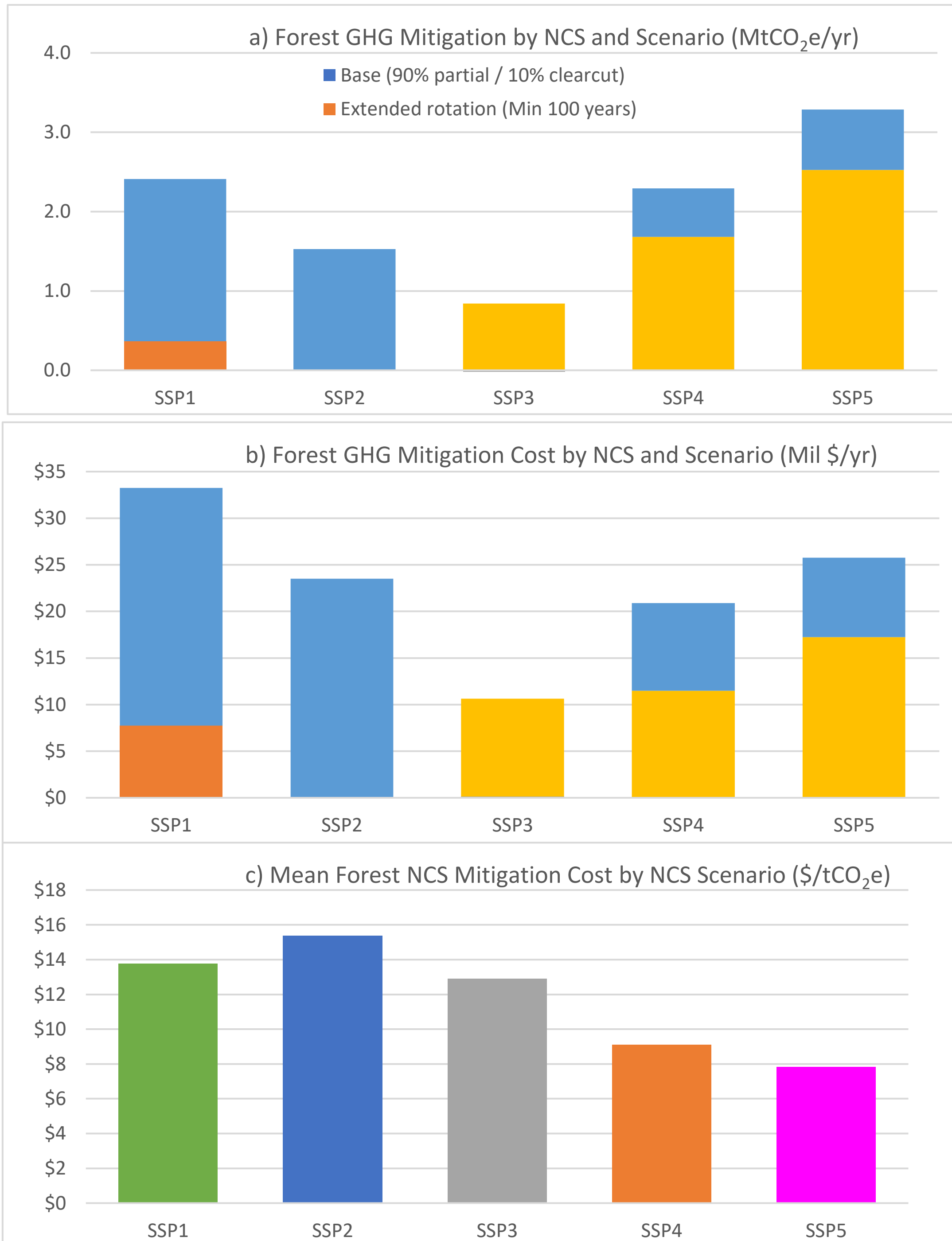


Figure 23a-c. Total annual forest GHG mitigation (a), total mitigation cost (b), and practice break-even carbon price ($/tCO₂e) by shared socioeconomic pathway (SSP) scenario.

3.4 Agriculture

3.4.1 Model Baseline

The agricultural sector model baseline estimates are listed in Table 15. We estimated that the 355,561 acres of major crops and 30,443 head of dairy cattle in the state collectively produced about $850 million in revenue per year, or about $246 million/yr in net revenue once capital and operating expenses are taken into account. These baseline farm enterprises emitted about 320,000 tCO_2e/yr of GHGs, but they also sequestered about 42,000 tCO_2e/yr through activities such as no-till and cover cropping.

The baseline Maine agricultural sector GHGs and carbon sequestration are shown in Figure 24. When adding the 67,000 tCO_2e/yr of non-dairy livestock emissions to our estimates in Table 15, we estimated that gross GHG emissions are equal to about 387,127 tCO_2e/yr, while carbon sequestration from current NCS practices reduced the sector footprint by 42,345 tCO_2e/yr. For comparison, DEP (2020) estimates Maine's 2017 agricultural sector gross GHG emissions to be 380,000, or just 2% lower than our gross GHG estimate.

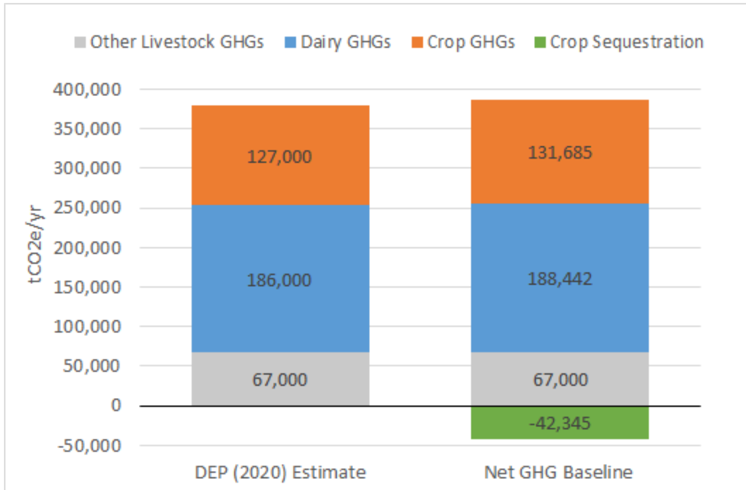


Figure 24. Maine DEP (2020) and modeled baseline agricultural sector GHG emissions.

Table 15. Key Maine agricultural sector model baseline estimates.

Crop	Area (acres) / Head (cattle)	Revenue (Mil $/yr)	Cost (Mil $/yr)	Net Revenue (Mil $/yr)	Gross GHG (tCO_2e/yr)	Carbon Sequestration (tCO_2e/yr)	Net GHG (tCO_2e/yr)
Hay	175,231	$173.9	$56.5	$117.4	0	7,072	-7,072
Potato	50,211	$126.0	$69.4	$56.7	20,184	10,801	9,382
Blueberries	38,660	$81.3	$58.1	$23.1	12,513	0	12,513
Wheat	19,710	$16.6	$6.2	$10.5	20,445	4,220	16,225
Corn	32,571	$12.0	$18.7	-$6.7	39,297	14,406	24,891
Barley	19,710	$4.6	$7.3	-$2.7	3,625	4,220	-594
Vegetables	12,028	$266.0	$207.8	$58.2	18,998	1,626	17,373
Apples	7,441	$61.0	$44.4	$16.6	16,622	0	16,622
Crop Total	355,561	$741.5	$468.4	$273.0	131,685	42,345	89,340
Dairy	30,443	$108.6	$135.2	-$26.6	188,442	0	188,442
Major Ag Sector Total	355,561	$850.1	$603.6	$246.4	320,127	42,345	277,782

3.4.2 Agriculture NCS Practice Results

Applying our core (i.e., 'medium') agricultural sector model assumptions about NCS adoption, mitigation potential, yield change, and practice costs, we estimate that there is wide variation in the potential benefits from implementing agricultural NCS in Maine (Figure 25). According to our results, the largest mitigation potential comes from the application of biochar, which could yield nearly 570,000 tCO_2e/yr, followed by permanent conversion from managed cropland and pasture to non-harvested perennial grass (363,255 tCO_2e/yr). Both practices could be implemented at relatively low cost, in the range of \$25-34/tCO_2e (Table 9). These large mitigation potentials are primarily a result of two factors. First, both practices have relatively high per-acre carbon sequestration rates. Second, the two NCS practices apply to a wide range of crops, including hay, which makes up the largest proportion of Maine's total crop area.

Many of the other practices considered for this study yielded relatively low total mitigation or were relatively costly. Cover crops and reduced-intensity tillage practices yielded between 13,423 and 32,755 tCO_2e/yr due to low area applicability and low rates of carbon accumulation (0.1 to 0.4 t/ac/yr) on a per-acre basis. However, we note that our study only focused on the climate mitigation and yield impacts of implementing these practices, though they are likely to also produce co-benefits such as improved soil health and water quality.

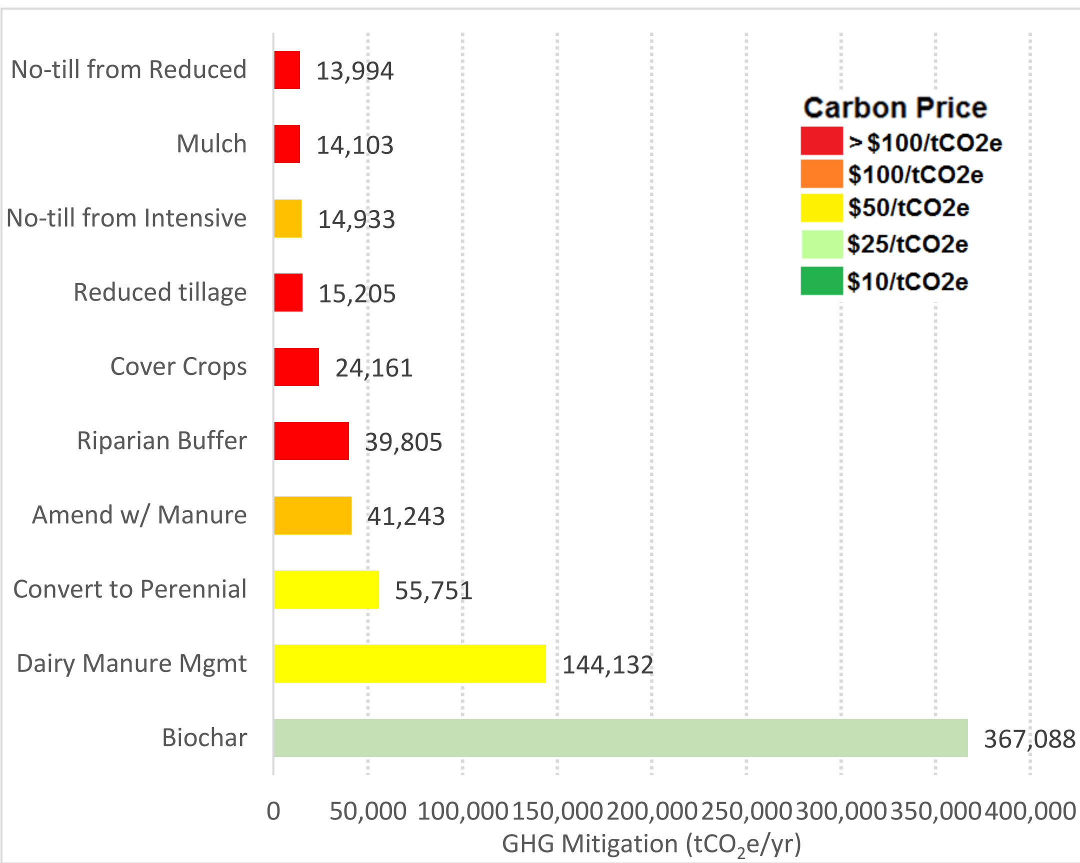


Figure 25. Total Maine agriculture NCS mitigation potential (tCO_2e/yr).

Table 16. Maine agricultural NCS practice estimates by crop.

NCS Practice	Hay	Potato	Blueberries	Wheat	Corn	Barley	Vegetables	Apples	Dairy	Total
Annual Mitigation (tCO_2e/yr)										
No-till from Intensive	0	0	0	57	14,820	57	0	0	0	14,933
No-till from Reduced	0	0	0	6,997	0	6,997	0	0	0	13,994
Reduced tillage	0	8,147	0	1,299	3,257	1,299	1,203	0	0	15,205
Cover Crops - non-legume	0	6,527	0	2,562	4,234	2,562	1,564	0	0	17,450
Cover Crops - legume	0	11,549	0	4,533	7,491	4,533	2,766	0	0	30,873
Cover Crops - mixed	0	9,038	0	3,548	5,863	3,548	2,165	0	0	24,161
Biochar	140,185	59,990	46,392	23,651	39,085	31,535	17,320	8,929	0	367,088
Amend w/ Manure	13,580	7,783	5,992	3,055	5,049	3,055	1,864	865	0	41,243
Convert to Perennial	33,784	7,644	0	3,444	6,105	2,183	2,591	0	0	55,751
Mulch	0	0	12,371	0	0	0	1,732	0	0	14,103
Dairy Manure Management	0	0	0	0	0	0	0	0	144,132	144,132
Riparian Buffer	28,789	7,690	0	476	1,629	384	836	0	0	39,805
Annual Mitigation Cost (Mil $/yr)										
No-till from Intensive	$0.0	$0.0	$0.0	$0.0	$0.6	$0.0	$0.0	$0.0	$0.0	$0.6
No-till from Reduced	$0.0	$0.0	$0.0	$1.7	$0.0	$0.7	$0.0	$0.0	$0.0	$2.4
Reduced tillage	$0.0	$1.8	$0.0	-$0.1	$0.6	$0.3	$0.3	$0.0	$0.0	$2.9
Cover Crops - non-legume	$0.0	$3.2	$0.0	$2.8	$1.8	$1.6	$0.8	$0.0	$0.0	$10.0
Cover Crops - legume	$0.0	$3.2	$0.0	$1.3	$1.4	$1.3	$0.8	$0.0	$0.0	$7.9
Cover Crops - mixed	$0.0	$3.7	$0.0	$2.3	$2.0	$1.6	$0.9	$0.0	$0.0	$10.5
Biochar	$3.6	$1.5	$1.2	$0.6	$1.0	$0.8	$0.4	$0.2	$0.0	$9.3
Amend w/ Manure	$1.2	$0.7	$0.5	$0.3	$0.4	$0.3	$0.2	$0.1	$0.0	$3.6
Convert to Perennial	$1.2	$0.2	$0.0	$0.1	$0.2	$0.1	$0.1	$0.0	$0.0	$1.8
Mulch	$0.0	$0.0	$77.3	$0.0	$0.0	$0.0	$10.8	$0.0	$0.0	$88.1
Dairy Manure Management	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$4.3	$4.3
Riparian Buffer	$3.6	$0.7	$0.0	$0.1	$0.2	$0.1	$0.1	$0.0	$0.0	$4.6
Break-even Carbon Price ($/$tCO_2e$)										
No-till from Intensive	$0	$0	$0	$189	$41	$73	$0	$0	$0	$41
No-till from Reduced	$0	$0	$0	$243	$52	$94	$0	$0	$0	$168
Reduced tillage	$0	$218	$0	-$61	$198	$229	$218	$0	$0	$191
Cover Crops - non-legume	$0	$483	$0	$1,080	$415	$614	$483	$0	$0	$573
Cover Crops - legume	$0	$273	$0	$295	$189	$278	$273	$0	$0	$256
Cover Crops - mixed	$0	$412	$0	$641	$334	$462	$412	$0	$0	$434
Biochar	$25	$25	$25	$25	$25	$25	$25	$25	$0	$25
Amend w/ Manure	$88	$88	$88	$88	$88	$88	$88	$88	$0	$88
Convert to Perennial	$34	$21	$0	$30	$28	$48	$24	$0	$0	$31
Mulch	$0	$0	$6,250	$0	$0	$0	$6,250	$0	$0	$6,250
Dairy Manure Management	$0	$0	$0	$0	$0	$0	$0	$0	$30	$30
Riparian Buffer	$124	$86	$0	$106	$103	$132	$95	$0	$0	$115

The Maine agricultural NCS model estimates by specific crop are summarized in Table 16. This table highlights how the overall carbon sequestration potential of some agricultural management practices is limited by the small amount of land in crop production. Furthermore, it demonstrates that mitigation may come from a wide range of crops.

All of these practices are presented as a single practice implementation on a given parcel of land. In reality, some of these practices can be applied simultaneously. Furthermore, the dairy manure management practices do not overlap with the crop practices. Thus, Maine farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure. If these options were simultaneously implemented across all eligible farms, then Maine could expect to mitigate up to 566,000 tCO_2e/yr in agricultural GHG emissions or nearly 1.5 times the sector's current annual emissions. This combined approach is

Table 17. Dairy manure management NCS summary.

Estimate	Large Complete Mix Anaerobic Digester (AD) with electricity generation	Covered Lagoon/ Holding Pond AD with electricity generation	Solid-liquid separation (SLS)	Small Complete Mix AD with electricity generation	Plug Flow AD with electricity generation
Total constructed (no.)	12	100	30	100	100
Total GHG Mitigation (tCO_2e/yr)	148,800	209,700	244,860	148,800	128,700
Total Mitigation Cost ($/yr)	$922,221	$9,329,591	$1,866,098	$5,290,110	$9,251,873
Break-even Carbon Price ($/$tCO_2e$)	$6	$44	$8	$36	$72

estimated to cost $18.9 million/yr or about $33/$tCO_2e$. Future research will explore the technical and financial feasibility of creating different bundles of practices for agricultural NCS.

The dairy manure management estimates summarized above were based on the assumptions that Maine's dairy farms collectively implemented a mix of the five different dairy NCS practices under consideration (Table 17). Breaking out dairy by specific NCS practices, which were primarily different sizes and types of anaerobic digesters (AD), reveals that the larger-impact options (i.e., complete mix AD and SLS) were the most cost-effective, yielding break-even carbon prices of $6-8/$tCO_2e$. However, these two practices would also need to rely on manure from several dairy farms. This is the case for the Summit Utilities, Inc., anaerobic digester being constructed in Clinton, which is expected to collect waste from up to 17% of the state's dairy herd (Summit Utilities Inc., 2019). However, our results may be optimistic for Maine's dairy sector, which often consists of small herds (USDA NASS, 2019). As a result, widespread implementation will likely require extensive cooperation, capital investment, and potentially long waste hauling distances to large digesters.

The model estimates were dependent on a wide range of assumptions about how NCS practices affect yield, cost, and mitigation potential.[27] As a result, we conducted a sensitivity analysis that tested the effect of our assessment when the core (medium) assumptions were modified to a low and high input cost and yield impact case. The analysis indicates that the mitigation costs were most sensitive for reduced tillage, biochar, conversion to perennial set-asides, and manure management (Figure 26, Figure 27). However, biochar and manure management were still estimated to be relatively cheap, even under the high-cost case, and thus should not be ruled out even if actual costs are higher than our core assumptions. If we apply the same list of feasible practices discussed above across Maine's farms, then we estimate a low total (break-even) cost of $11.7 mil/yr ($21/tCO_2e) and a high cost of $33.9 mil/yr ($60/tCO_2e). While this cost range is found to be higher than that of most of the forest NCS practices, it still falls within the range defined in other NCS and land-based mitigation studies (Fargione et al., 2018; Griscom et al., 2017; Roe et al., 2019), and it is comparable to the cost of implementing non-NCS options like renewable energy (Riahi et al., 2017).

[27] N.B., for this analysis we opted to exclude a low and high mitigation sensitivity due to the extreme range in emissions scenarios published in the literature. We hope to explore this impact in a future analysis.

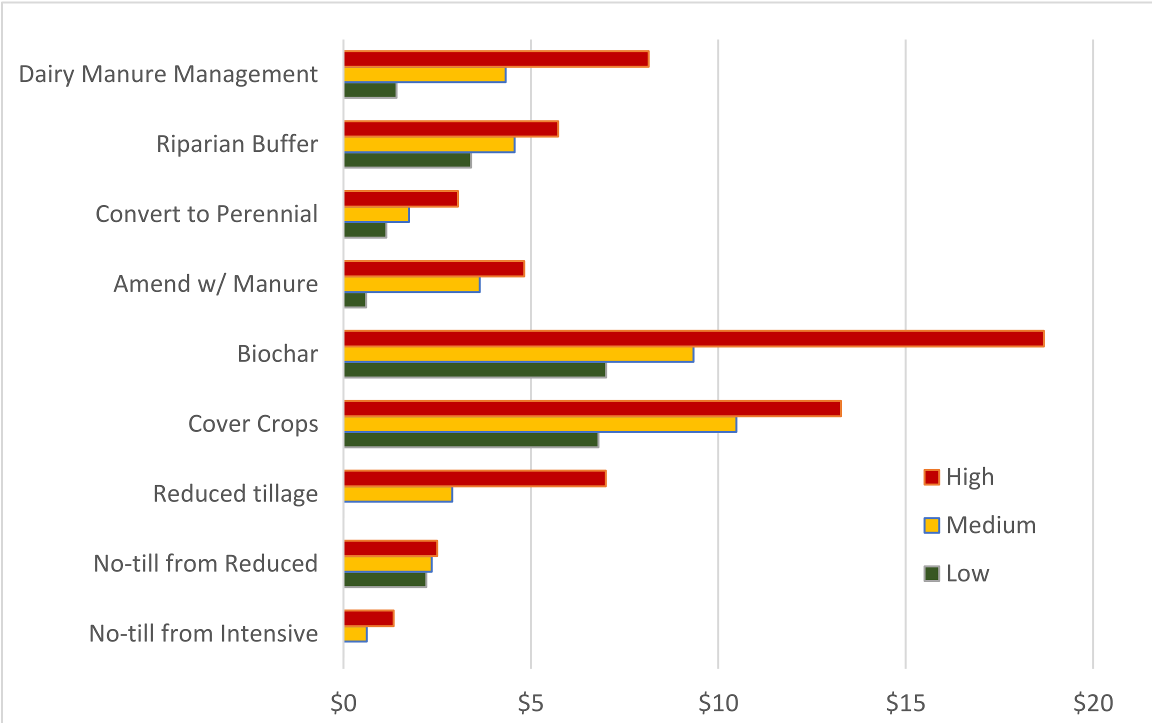


Figure 26. Total annual Maine agriculture NCS practice cost (mil $/yr) by sensitivity case.

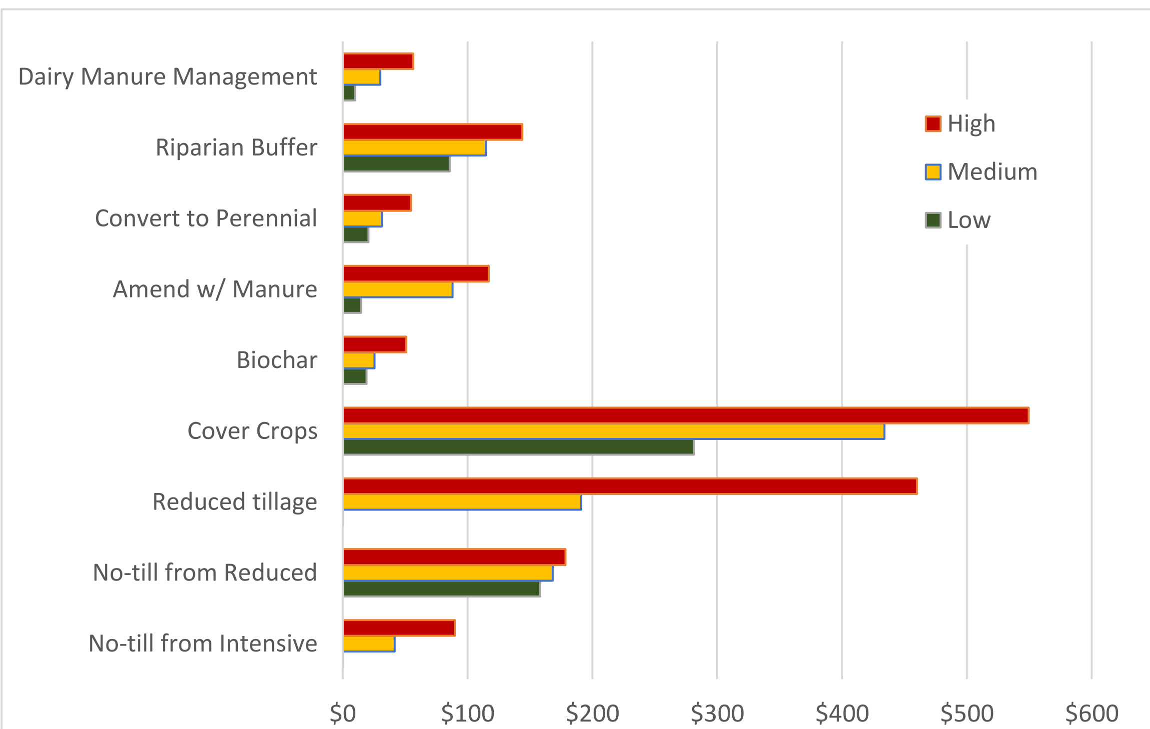


Figure 27. Total annual Maine agriculture NCS practice break-even carbon price ($/t$CO_2$e) by sensitivity case.

3.4.3 Avoided Cropland Conversion

Data from two sources indicated that between 1,190 and 1,560 acres of agricultural land in Maine has been converted on an annual basis over the past 15 years (Table 18; Freedgood et al., 2020; Lark et al., 2020). According to American Farmland Trust (AFT; Freedgood et al., 2020), approximately 81% of this land was converted to low density residential, while the remaining 19% was highly developed. Furthermore, about 48% of the converted agricultural land was classified as cropland, followed by woodland (37%), and grassland (37%). Purchasing the same amount of land on an annual basis to avoid conversion is estimated to cost $3.2-4.5 million/yr, or a mean of $2,026-$3,810/acre. As indicated in the methodology, we did not analyze whether there would be any substantial GHG benefits from avoiding the conversion of agricultural land to development, although it is probable that conserving some land could have a net reduction in emissions relative to its alternative use.

Table 18. Estimated annual area and cost of avoided cropland conversion in Maine.

County	Avoided Conversion Area (ac/yr)		Annual Cost to Avoid Conversion ($/yr)	
	American Farmland Trust (2020)	*Lark et al (2020)*	*American Farmland Trust (2020)*	*Lark et al (2020)*
Washington	4	160	$3,948	$173,899
Hancock	36	21	$70,463	$40,491
Knox	13	30	$148,014	$344,636
Kennebec	168	100	$804,591	$478,718
Waldo	82	77	$229,332	$215,929
Lincoln	16	21	$107,177	$141,638
Sagadahoc	37	6	$408,885	$67,907
Cumberland	78	38	$1,397,057	$677,188
York	73	23	$787,986	$245,747
Penobscot	63	208	$52,451	$173,673
Somerset	281	83	$205,291	$60,481
Oxford	25	23	$36,184	$33,920
Aroostook	250	639	$81,551	$208,584
Piscataquis	14	77	$7,865	$43,501
Franklin	16	5	$19,446	$6,074
Androscoggin	31	48	$160,560	$244,627
Maine Total	**1,187**	**1,558**	**$4,520,802**	**$3,157,013**

3.4.4 Agriculture Shared Socioeconomic Pathways

As with the forest sector shared socioeconomic pathways, we estimated a wide range in impacts across the five agricultural SSPs. Total mitigation from agriculture ranges from 0.01 for SSP3, which has very limited adoption of NCS practices, to 0.59 $MtCO_2e$/yr for SSP5, which includes a broad mix of practices (Figure 28a-c). The total GHG mitigation costs thus range from $3-29 mil/yr, with the highest costs occurring in the pathways with stronger adoption. While SSP3 has the least absolute costs because of limited action to mitigate climate change, the focus on only implementing cover crops results in a break-even cost of $425/$tCO_2e$. All the other SSPs rely on biochar and manure management to achieve the bulk of reductions in GHGs. As a result, the average break-even carbon prices for the four other SSPs range between $24 and $51/$tCO_2e$ across the SSPs.

In terms of their contribution to offsetting or reducing the agricultural sector's annual emissions of about 0.4 $MtCO_2e$/yr, SSPs 1 and 5 could achieve carbon neutrality (negativity) for the sector at a respective cost of $29 and $25 mil/yr. In addition, both SSPs 2 and 4 are also likely to see noticeable reductions in net sector emissions, largely from investments in cost-effective practices like biochar and manure management. SSP4 could produce a 70% reduction in the sector's current emissions at a cost of $14 mil/yr, while SSP2 could reduce emissions by 56% at a cost of $5.3 million/yr. This finding highlights the potential cost-effectiveness of reducing the sectors GHGs that could be achieved from even a moderate uptake of emerging NCS practices.

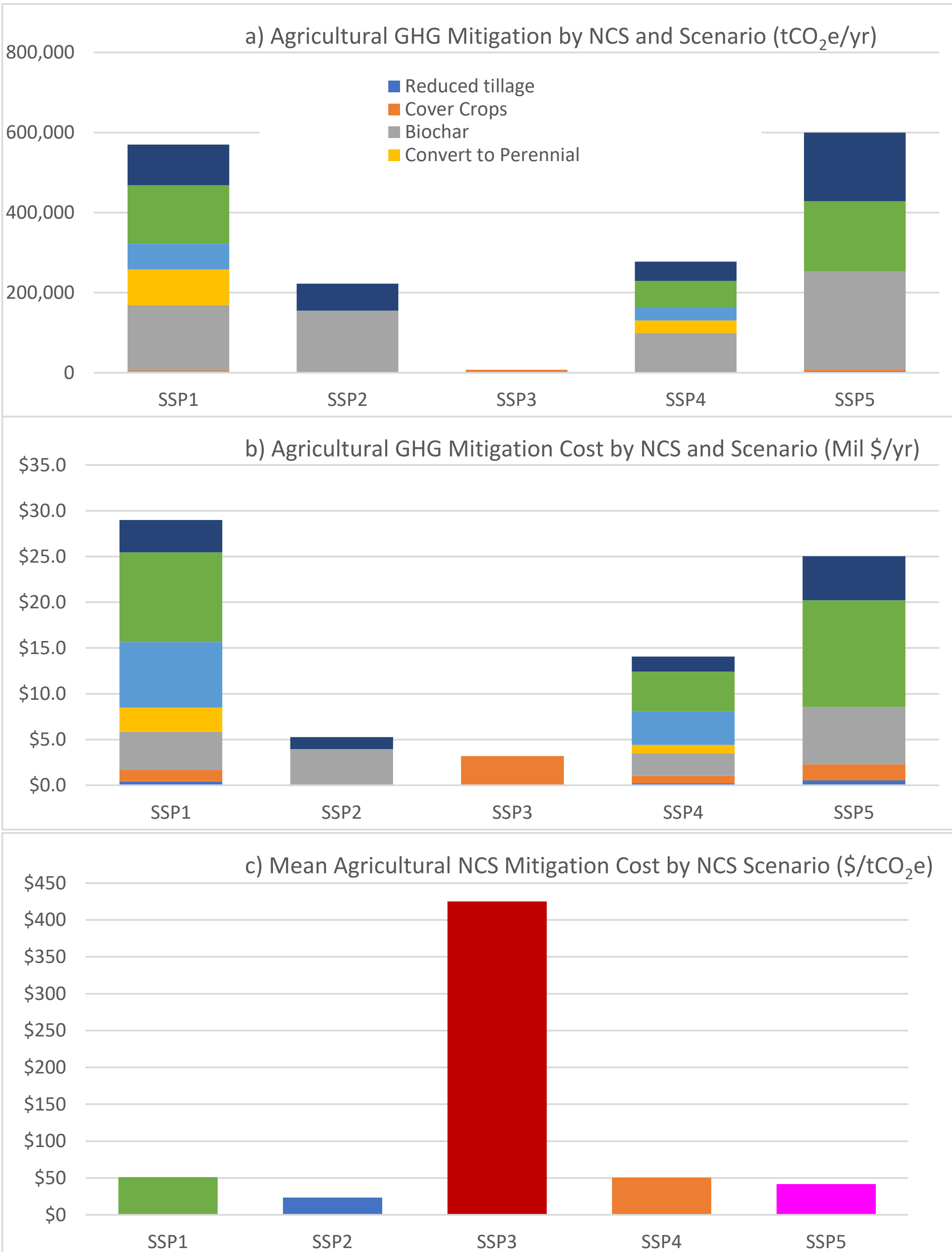


Figure 28a-c. Total annual Maine agriculture total GHG mitigation (a), total mitigation cost (b), and practice break-even carbon price ($/$tCO_2e$) by shared socioeconomic pathway (SSP) scenario.

4. Summary & Conclusions

This study sought to estimate the financial costs and GHG mitigation benefits of implementing a range of NCS practices across Maine's farms and forests. A summary of the key findings is listed in Table 19. Based on this assessment, we found that among a selection of practices evaluated, the following five practices for each of the forestry and agriculture sectors provided the most mitigation potential in Maine at relatively low cost.

Forestry:	Agriculture:
1. Shift harvest areas to include more intensive management 2. Combine clearcut harvests with planting 3. Increase set asides to increase continuous standing carbon 4. Avoid forest conversion 5. Afforest marginal cropland and pasture	1. Amend soil with biochar 2. Manage dairy manure 3. Convert to perennial grasses 4. Amend soil with manure 5. Plant riparian buffers

The results in Table 19 present the impacts if specific practices were implemented on their own in Maine based on the aerial extent of relevant land areas. However, in some instances, a subset of NCS practices can be implemented simultaneously on the same ownership, either on the same farm/stand or in separate areas, which will be explored in more detail in a future analysis. Also, a diversity of approaches and practices are expected to be applied across a variety of land ownerships. Hypothetically, on forested land, collectively changing forest management across 9.1 million acres in northern Maine to 50% clearcut followed by planting in addition to afforesting marginal land and reducing conversion of forests to cropland across the state could yield about 5.3 $MtCO_2e$/yr in additional carbon sequestration at a cost of $79 million/yr or $15/$tCO_2e$. For Maine agriculture, farmers could collectively amend their soil with biochar, reduce their tillage intensity, plant riparian buffers, and construct and utilize anaerobic digesters to manage dairy manure waste, thereby mitigating up to 566,000 tCO_2e/yr in GHG emissions or nearly 1.5 times the sector's current annual emissions. This combined approach for the agricultural sector – assuming all eligible farms implement these practices across the state – is estimated to cost $18.9 million/yr or $33/$tCO_2e$.

With respect to forestry, our analysis found that a variety of NCS scenarios reduced annual harvests by 5% or less compared to the BAU, thereby ensuring a relatively steady timber supply even with an increase in forest carbon sequestration. The key exception is the scenario with the constraint that stands must be at least 100 years old to harvest. As harvests in most scenarios were close to BAU, there was also minimal risk of leakage in the form of increased harvests and lost forest carbon outside of our study area. Our study also found that there are potential habitat tradeoffs with increased clearcuts and planting versus natural regeneration. Finally, we note that the average break-even carbon prices that we estimated for the sector are in the range of $10-20/$tCO_2e$. These prices are relatively inexpensive compared to typical carbon prices for other sectors of the economy and social cost of carbon estimates, thus indicating that application of NCS practices in Maine's forest sector could be a cost-effective option to help meet the state's greenhouse gas reduction goals.

Table 19. Summary of key findings for Maine NCS mitigation potential.

Land-use Sector	NCS Practice	GHG Mitigation (tCO_2e/yr)	Mitigation Cost (mil $/yr)	Break-even Carbon Price ($\$/tCO_2e$)	Total Applicable Area (acres or cows)*
Forestry	BAU age (min 50)	0	$0	$0	9,100,000
	Min 85 years	-8,442	-$2	$17	9,100,000
	Min 100 years	746,175	$17	$14	9,100,000
	35% Clearcut (CC)	-72,742	$1	$8	9,100,000
	50% Clearcut (CC)	135,279	$6	$12	9,100,000
	35% CC, plant	2,450,892	$24	$11	9,100,000
	50% CC, plant	3,487,249	$37	$11	9,100,000
	10% set aside	446,478	$9	$23	9,100,000
	20% set aside	1,059,718	$22	$24	9,100,000
	35% CC, plant, 10% set aside	2,717,633	$32	$12	9,100,000
	35% CC, plant, 20% set aside	3,061,775	$42	$14	9,100,000
	Afforestation	759,617	$23	$30	360,000
	Avoided Forestland Conversion	1,101,003	$19	$17	257,500
Agriculture	No-till from Intensive	14,933	$0.6	$41	32,820
	No-till from Reduced	13,994	$2.4	$168	39,419
	Reduced tillage	15,205	$2.9	$191	152,048
	Cover Crops	24,161	$10.5	$434	134,229
	Biochar	367,088	$9.3	$25	229,430
	Amend w/ Manure	41,243	$3.6	$88	266,085
	Convert to Perennial	55,751	$1.7	$31	34,686
	Riparian Buffer	39,805	$4.6	$115	21,309
	Mulch	14,103	$88.1	$6,250	44,072
	Large Complete Mix AD	150,997	$0.9	$6	30,443
	Covered Lagoon/Holding Pond AD	212,797	$4.1	$19	30,443
	Solid-liquid separation (SLS)	129,565	$1.9	$8	30,443
	Small Complete Mix AD	150,997	$5.4	$36	30,443
	Plug Flow AD	76,305	$9.4	$72	30,443

**While we model 9.1 million acres of forest in Northern Maine, biophysical and/or policy constraints limit the entire area from being able to implement each NCS. For example, approximately 6% of the study area is currently unable to be harvested due to these constraints.*

For Maine agriculture our results point to a high mitigation potential from amending soil with biochar, converting cropland and pasture to perennial grasses, and constructing anaerobic digesters for dairy manure management. There is abundant literature from throughout the globe on the potential effect of biochar on reducing GHG emissions, but it is less established as a common practice at the commercial scale, especially in conditions such as Maine. In addition, converting land to perennial grasses could potentially take cropland out of production, thereby reducing the amount of locally sourced food available to Mainers with consequences for other aspects of Maine's climate response. Dairy management relies on an investment in digesters, which require financial capital that can prove challenging. Despite these uncertainties, Maine's agricultural sector has the potential to reduce its within-sector emissions or even be net-negative as a sector while enhancing the sustainability and health of Maine's farms and food systems.

We note that there are some important model limitations that could be addressed in future research applied to our forestry NCS assessment. First, the LANDIS-based model estimates were based on only a single run for each scenario that quasi-randomly selected which stands to harvest and/or plant. Conducting multiple model runs for the same management scenario would provide additional insight on the level of uncertainty surrounding the carbon estimates. The second limitation is that the analysis only covered the northern half of the state. To provide a statewide context for our estimates, we incorporated carbon information derived from US Forest Service Forest Inventory and Analysis (FIA) data for areas outside our project study area (Appendix C). Encompassing the carbon dynamics of southern Maine to a degree equal to the efforts demonstrated here for northern Maine should be a priority for future research. Third, models of future forest response to climate are constantly evolving, and future research could apply more robust analyses taking into consideration greater mechanistic complexities of forest change.

Our results show limited carbon sequestration of the agricultural NCS practices in Maine compared to forestry. Our model only assessed their impact on yield and net GHG emissions and no co-benefits such as the provision of other ecosystem services, improved climate change adaptation, and enhanced farm resilience. Further, locally collected data were often unavailable to inform our modeling approach, so many parameter values were drawn from regional estimates or extrapolated from growing systems with similarities to Maine, as detailed in our methods description. Additional biophysical research specific to NCS practice application in Maine crops and cropping systems is needed to better understand local yield impacts and soil carbon sequestration dynamics for both current and future climates. Further research could incorporate quantification of the potential co-benefits of NCS on things like water quality and quantity and soil and human health. Currently, farmers often implement NCS practices to improve in water quality, quantity, and soil health to make their farm systems more adaptive and resilient to climate change, but there is a need for further research to explore the relationship between different practices and these interactions and effects. The analysis could also be extended to investigate interactions between the forestry and agricultural sectors.

In the interest of calculating theoretical maximum results, our core analysis assumed that most practices would be fully implemented across all eligible land. In reality, not every farmer and forest landowner will have the technical and financial resources – or the inclination in light of their own circumstances and ownership objectives – to undertake some of these practices. Legal constraints may also preclude certain practices on some ownerships or portions of ownerships. For example, while we found biochar to be an extremely cost-effective opportunity for Maine's agricultural sector, particularly given the abundance of raw materials available to produce biochar, very few farmers are currently implementing this on their land in Maine. As a result, we used interviews and focus groups to explore the potential technical, financial, social, and/or policy barriers and opportunities that stakeholders face in implementing the NCS practices presented in this report that may limit Maine's ability to reach the estimated GHG mitigation potential, which were then used to establish a range of constraints and scenarios to consider as a form of sensitivity analysis.

Finally, we offer two closing thoughts on this study. First, while there is a tremendous body of knowledge in the literature upon which to draw to undertake these technical analyses, it is essential to support Maine decision-makers with Maine-based data and experience given the unique historical, biophysical, and socioeconomic character of Maine. Maine's spruce-forests are not like southern pine and Maine's potato production systems and markets are not like California's. Second, while most of these NCS have important contributions to make to the urgently needed reduction of atmospheric greenhouse gas concentrations (as they simultaneously provide vital co-benefits often referred to as "ecosystem services"), it must be noted that most of these contributions are finite: we can increase carbon in forests and soils up to a point, but not forever. This means that NCS contributions between now and mid-century are the most critical for investment.

Appendix A. Detailed Results

Table 20. Maine forest NCS estimates for core (medium) analysis, 20 and 50-year means.

Scenario	Total Carbon Above Baseline (tCO_2e/yr)	Harvest Volume (gt/yr)	Mitigation Cost ($/yr)	Break-even Carbon Price ($/$tCO_2e$)
20 Year Mean (2020-2040)				
BAU age (min 50)	0	9,471,768	$0	n/a
Min 85 years	913,691	8,521,344	$12,625,887	$15
Min 100 years	3,443,104	5,173,162	$57,104,742	$17
35% Clearcut (CC)	290,658	8,998,829	$6,282,743	$4
50% Clearcut (CC)	823,206	8,263,340	$16,053,339	$22
35% CC, plant	2,062,485	8,993,230	$30,016,958	$16
50% CC, plant	3,174,681	8,267,601	$47,545,797	$16
10% set aside	545,455	8,767,195	$9,359,881	$17
20% set aside	1,319,411	7,793,476	$22,295,233	$17
35% CC, plant, 10% set aside	2,459,216	8,326,006	$37,294,950	$16
35% CC, plant, 20% set aside	3,017,038	7,397,059	$31,656,718	$16
Afforestation	735,443	9,471,768	$22,063,299	$30
Avoided Forest Conversion	1,101,003	9,471,768	$18,620,590	$17
50 yr mean (2020-2070)				
BAU age (min 50)	0	9,588,961	$0	n/a
Min 85 years	-8,442	9,735,567	-$1,947,585	$17
Min 100 years	746,175	8,337,878	$16,619,979	$14
35% Clearcut (CC)	-72,742	9,546,595	$562,806	n/a
50% Clearcut (CC)	135,279	9,132,060	$6,069,685	$12
35% CC, plant	2,450,892	9,556,441	$24,091,876	$11
50% CC, plant	3,487,249	9,156,458	$37,292,690	$11
10% set-aside	446,478	8,892,050	$9,258,097	$23
20% set-aside	1,059,718	7,909,976	$22,304,440	$24
35% CC, plant, 10% set aside	2,717,633	8,867,593	$31,656,718	$12
35% CC, plant, 20% set aside	3,061,775	7,888,042	$42,177,904	$14
Afforestation	759,617	9,588,961	$22,788,513	$30
Avoided Forest Conversion	1,101,003	9,588,961	$18,620,590	$17

Table 21. Maine agricultural NCS estimates by sensitivity case.

NCS Practice	Total Mitigation (tCO_2e/yr)			Total Cost (Mil $/yr)			Break-Even Price ($/$tCO_2e$)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
No-till from Intensive	n/a	14,933	n/a	-$0.10	$0.62	$1.34	-$7	$41	$90
No-till from Reduced	n/a	13,994	n/a	$2.21	$2.36	$2.50	$158	$168	$178
Reduced tillage	n/a	15,205	n/a	-$0.37	$2.90	$7.00	-$24	$191	$460
Cover Crops	n/a	24,161	n/a	$6.80	$10.48	$13.28	$281	$434	$549
Biochar	n/a	367,088	n/a	$7.01	$9.34	$18.68	$19	$25	$51
Amend w/ Manure	n/a	41,243	n/a	$0.61	$3.63	$4.82	$15	$88	$117
Convert to Perennial	n/a	55,751	n/a	$1.14	$1.75	$3.05	$21	$31	$55
Riparian Buffer	n/a	39,805	n/a	$3.41	$4.57	$5.73	$86	$115	$144
Mulch	n/a	14,103	n/a	$66.11	$88.14	$110.18	$4,688	$6,250	$7,813
Dairy Manure Mgmt	n/a	144,132	n/a	$1.42	$4.33	$8.14	$10	$30	$56

Table 22. Maine forest sector estimates by shared socioeconomic pathway.

NCS Practice	SSP1	SSP2	SSP3	SSP4	SSP5
Maine Forest NCS Area by SSP (Mil acres)					
Base (90% partial / 10% clearcut)	0.0	4.6	4.6	2.7	0.0
Extended rotation (Min 100 years)	2.3	0.0	0.0	0.0	0.0
35% clearcut	0.0	0.0	2.3	0.0	0.0
50% clearcut + plant	0.0	0.0	2.3	4.6	6.8
35% CC & plant + 20% Set Aside	6.8	4.6	0.0	1.8	2.3
Study Area Total	9.1	9.1	9.1	9.1	9.1
Change in Total Forest C by SSP (mil tCO_2e/yr)					
Base (90% partial / 10% clearcut)	0.0	0.0	0.0	0.0	0.0
Extended rotation (Min 100 years)	0.4	0.0	0.0	0.0	0.0
35% clearcut	0.0	0.0	0.0	0.0	0.0
50% clearcut + plant	0.0	0.0	0.8	1.7	2.5
35% CC & plant + 20% Set Aside	2.0	1.5	0.0	0.6	0.8
Study Area Total	2.4	1.5	0.8	2.3	3.3
Change in Total Harvest by SSP (mil gt/yr)					
Base (90% partial / 10% clearcut)	0.0	0.0	0.0	0.0	0.0
Extended rotation (Min 100 years)	-0.3	0.0	0.0	0.0	0.0
35% clearcut	0.0	0.0	-0.1	0.0	0.0
50% clearcut + plant	0.0	0.0	-0.1	0.6	0.9
35% CC & plant + 20% Set Aside	-0.4	-0.9	0.0	-0.3	-0.1
Study Area Total	-0.7	-0.9	-0.2	0.2	0.7
Total Cost of GHG Mitigation by SSP (mil $/yr)					
Base (90% partial / 10% clearcut)	$0	$0	$0	$0	$0
Extended rotation (Min 100 years)	$8	$0	$0	$0	$0
35% clearcut	$0	$0	$0	$0	$0
50% clearcut + plant	$0	$0	$11	$12	$17
35% CC & plant + 20% Set Aside	$26	$24	$0	$9	$9
Study Area Total	$33	$24	$11	$21	$26
Average Break-Even Price ($/$tCO_2e$)					
Study Area Total	$14	$15	$13	$9	$8

Table 23. Maine agricultural sector estimates by shared socioeconomic pathway.

NCS Practice	SSP1	SSP2	SSP3	SSP4	SSP5
Maine Agriculture Area by SSP (acres)					
Base (No Mitigation)	64,129	291,033	386,824	236,094	82,919
Cover crops	16,339	0	41,802	11,029	22,670
Reduced tillage	24,508	0	0	11,029	30,227
Biochar	102,117	97,011	0	60,249	153,992
Convert to perennial grass	46,565	0	0	16,339	0
Riparian Buffer	32,269	0	0	16,543	0
Biochar + Cover Crops	81,693	0	0	36,762	98,236
Crop Total	367,621	388,044	428,626	388,044	388,044
Maine Dairy Stock Numbers by NCS and SSP (cows)					
Base (No Mitigation)	0	15,222	36,532	17,353	0
Large Complete Mix AD with elec gen	6,089	6,089	0	2,892	15,830
Solid-liquid separation (SLS)	6,089	6,089	0	2,892	7,915
Small Complete Mix AD with elec gen	6,089	1,522	0	2,892	7,915
Plug Flow AD with elec gen	6,089	1,522	0	2,892	7,915
Dairy Total	24,354	30,443	36,532	28,921	39,576
Change in Agricultural GHG Emissions by SSP (tCO_2e/yr)					
Reduced tillage	2,451	0	0	1,103	3,023
Cover Crops	2,941	0	7,524	1,985	4,081
Biochar	163,387	155,218	0	96,398	246,387
Convert to Perennial	89,005	0	0	31,326	0
Riparian Buffer	65,131	0	0	33,234	0
Biochar + Cover Crops	145,414	0	0	65,436	174,861
Dairy Manure Management	101,573	67,478	0	48,247	171,304
Maine Ag Sector Total	569,902	222,695	7,524	277,731	599,656
Total Cost of GHG Mitigation by SSP (mil $/yr)					
Reduced tillage	$0.4	$0.0	$0.0	$0.2	$0.5
Cover Crops	$1.3	$0.0	$3.2	$0.8	$1.7
Biochar	$4.2	$4.0	$0.0	$2.5	$6.3
Convert to Perennial	$2.6	$0.0	$0.0	$0.9	$0.0
Riparian Buffer	$7.2	$0.0	$0.0	$3.7	$0.0
Biochar + Cover Crops	$9.8	$0.0	$0.0	$4.4	$11.7
Dairy Manure Management	$3.5	$1.3	$0.0	$1.7	$4.8
Maine Ag Sector Total	$29.0	$5.3	$3.2	$14.1	$25.0
Average Break-Even Price ($/$tCO_2e$)					
Maine Ag Sector Total	$51	$24	$425	$51	$42

Appendix B. Detailed Input Data

Maine Forest Systems

Table 24. LANDIS baseline area by species, 2010.*

Species	Area (acres)
Red Maple	2,933,457
Balsam Fir	2,915,428
Yellow Birch	2,287,363
Red Spruce	2,244,374
Sugar Maple	1,933,383
Northern White Cedar	1,386,127
Paper Birch	1,264,980
American Beech	967,934
Eastern Hemlock	479,583
Black Spruce	462,059
White Ash	449,635
Eastern Whie Pine	449,049
White Spruce	326,810

**acres sum to more than the 10 million acres in total area covered by LANDIS because any given 30m pixel in the model can have anywhere from one to 13 species present.*

Maine Cropping Systems

The following section includes additional information on each of the agricultural enterprise systems and detailed budgetary information. For all of the enterprises, costs were adjusted to 2017 dollars based on the Producer Price Index (PPI) to account for inflation, and revenue is based on a 5-yr (2012-2017) average of the commodity price in Maine (*Crop Values Annual Summary*, 2020).

Apples

The financial budget for an apple system is calculated based on bearing fruit acres and was created based on economic information from a Cornell University study (Schmit et al., 2018).

Table 25. Apple orchard budget.

Component	Per bearing fruit acre
Revenue	
Yield (lbs):	30243.5
Price:	$0.31
Estimated Revenue	$8,196.00
Variable Costs	
Labor	$2,855.00
Chemical Inputs	$1,052.00
Insurance, Utilities, Interest, and professional/technical services	$541.00
Equipment expenses (fuel, oil, trucking, maintenance, leasing)	$481.00
Miscellaneous Expenditures	630
Total Variable Costs	$5,559.00
Fixed Costs	
Real estate costs (repair, taxes, and leasing)	$407.00
Total Costs	**$5,966.00**
Net Revenue	**$2,230.00**
Return over Variable Cost	**$2,637.00**

Barley

According to the 2017 USDA NASS Census of Agriculture, 15,115 acres of barley were grown for grain (2019). The financial budget for a typical barley cropping system assumes a farm of 26 planted acres. Costs were adapted from data from the USDA Economic Research Service for the Northeast region and were partly based on USDA's Agricultural Resource Management Survey (*Commodity Costs and Returns*, 2020). Table 26 summarizes the key revenues and costs for a typical Maine barley cropping system.

Table 26. Barley farm budget.

	Total	Per planted acre
Revenue		
Number of acres	26	
Yield (bu)	1248	48
Price ($/bu)	$3.87	
Primary product grain	$4,825.60	$185.60
Secondary product silage/straw/grazing	$871.55	$33.52
Annual Revenue	**$5,697.15**	**$233.25**
Variable costs		
Seed	$741.59	$28.52
Fertilizer [a]	$1,313.84	$50.53
Chemicals	$57.95	$2.23
Custom services	$699.20	$26.89
Fuel, lube, and electricity	$426.49	$16.40
Repairs	$504.51	$19.40
Other variable expenses [b]	$33.87	$1.30
Interest on operating inputs	$39.39	$1.51
Total Variable Costs	$3,816.85	**$146.80**
Fixed costs		
Hired labor	$54.44	$2.09
Opportunity cost of unpaid labor	$1,398.64	$53.79
Capital recovery of machinery and equipment	$1,651.27	$63.51
Opportunity cost of land	$2,281.23	$87.74
Taxes and insurance	$146.26	$5.63
General farm overhead	$337.43	$12.98
Total Fixed Costs	**$5,869.28**	**$225.74**
Total Costs	**$9,686.12**	**$372.54**
Net Revenue	**-$3,988.98**	**-$139.29**
Net Revenue over Variable Costs	**$1,880.30**	**$86.45**

[a] Cost of commercial fertilizers, soil conditioners, and manure.

[b] Cost of purchased irrigation water and straw baling.

Blueberries

Lowbush blueberries are clonal perennial shrubs that tolerate marginal, poorly drained sites, though most commercial production takes place on freely drained and often sandy soils, most commonly under acidic soil conditions. They are managed on a two-year cycle that utilizes mowing or (less commonly these days) burning in the non-production year to maximize floral initiation, fruit set, yield, and ease of mechanical harvest during the production year. About 70% of blueberry plants' biomass is found underground in rhizomes, which enables their recovery from biannual mowing or burning (Files et al., 2008). An average of 14 gallons of diesel fuel per acre are required for mowing, whereas 80 gallons of diesel fuel per acre is required for burning. Other important field operations and inputs include rental of honeybees for pollination during production years, use of N-P-K fertilizers, applications of sulfur (often applied at a concentration of 500-1,000 lbs/acre) (Files et al., 2008) to lower pH and manage weeds, application of herbicides, fungicides, and insecticides, and irrigation as needed during both production and non-production years (Yarborough, 2012).

According to former Extension wild blueberry specialist Dave Yarborough, opportunities for enhanced carbon sequestration in this crop may be limited because "wild blueberries do not store much biomass as plants are pruned every other year and there is a slow decomposition of the cut stems. Prior to the 1970s, plant[s] were burned with #2 fuel oil and so we had a much higher carbon emission in the past but now most are mowed; so most of the carbon benefits have been accrued in past years with this change in practice.[28] Use of soil amendments that will not raise soil pH such as modified biochars, as well as application of natural mulches are applicable NCS practices. Use of living mulches and cover crops in lowbush blueberry systems also represent areas of theoretical promise in which new research is currently being conducted.[29]

The financial budget for a typical blueberry cropping system was adapted from an enterprise budget prepared by the University of Maine Cooperative Extension (*Blueberry Enterprise Budget*, 2016) and reflects the following assumptions: a medium-yield conventional farm of 58 acres. Table 27 summarizes the key revenues and costs for a typical Maine blueberry cropping system.

Table 27. Lowbush blueberry farm financial budget.

	Total	($/Acre)	($/lb)
Revenue			
Number of Acres (Crop)	58.06		
Yield (lbs)	258,089		
Yield (lbs/acre)	4,445.21		
Price ($/lb)	0.47		
Annual Revenue	122,024.43	2,101.70	0.47
Variable Costs			
Pruning (burning and mowing)	$7,234	$125	$0.03
Weed Control	$7,471	$129	$0.03
Fertilization	$7,710	$133	$0.03
Pollination	$15,435	$266	$0.06
Pest Monitoring	$531	$9	$0.00
Insect Control	$5,806	$100	$0.01
Disease Control	$4,099	$71	$0.02
Irrigation	$0	$0	$0.00
Sulfur (pH)	$0	$0	$0.00
Harvest (raking and mechanical)	$46,448	$800	$0.14
Packing and Marketing	$0	$0	$0.00
Interest on Capital	$2,571	$44	$0.01
Blueberry Tax	$3,354	$58	$0.01
Total Variable Costs	**$100,659**	**$1,735**	**$0**
Total Costs	**$100,659**	**$1,735**	**$0.34**
Net Revenue	**$21,365**	**$367**	**$0.13**

[28] D. Yarborough, personal communication, January 27, 2020.

[29] L. Calderwood, personal communication, January 9, 2020.

Corn

According to the 2017 USDA NASS Census of Agriculture, 7,237 acres of corn were grown for grain and 25,344 acres were grown for corn silage (2019). Silage corn is planted at soil temperatures above 50° F, typically takes 70-95 days to grow to maturity, and yields 18-30 tons per acre of 30% dry matter feed.[30] No-till (NT) and reduced-tillage (RT) practices are applicable to this crop, and biochar and set -aside programs may be as well. After harvest, silage corn is typically stored for fermentation in bunkers or silos. The financial budget is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide et al., 2004) and assumes a 160 acre farm. Table 28 summarizes the key revenues and costs for a typical Maine grain corn cropping system.

Table 28. Corn farm financial budget.

	Total	Per Acre	Per Bu
Revenue			
Number of Acres	160		
Grain Corn Yield (bu)	16,000	100	
Price ($/bu)	$3.69		
Annual Revenue	$59,008	$368.80	$3.69
Variable Costs			
Seed	$5,918	$36.99	$0.37
Fertilizer	$14,434	$90.21	$0.90
Lime	2677.433	$16.73	$0.17
Chemicals	$5,382	$33.64	$0.34
Labor	$8,121	$50.75	$0.51
Diesel Fuel and Oil	$2,853	$17.83	$0.18
Maintenance and Upkeep	$5,221	$32.63	$0.33
Supplies	$2,207	$13.79	$0.14
Insurance	$73	$0.46	$0.00
Utilities	$441	$2.76	$0.03
Rent or Lease	$2,759	$17.24	$0.17
Drying	$4,264	$26.65	$0.27
Interest	$1,501	$9.38	$0.09
Total Operating Expenses	**$55,851**	**$349.07**	**$3.49**
Fixed Costs			
Depreciation and Interest	$33,493	$209.33	$2.09
Tax and Insurance	$2,444	$15.28	$0.15
Total Ownership Expenses	**$35,938**	**$224.61**	**$2.25**
Total Annual Cost	**$91,789**	**$573.68**	**$5.74**
Net Farm Income (NFI)	-$32,781	-$204.88	-$2.05
Return over Variable Cost (ROVC)	$3,157	$19.73	$0.20

Dairy

The dairy production cycle begins with the birth of a calf, which induces milk production. Milk is harvested for a 10-12 month period, which overlaps with the first seven months of the next nine-month gestation period. The last two months prior to calving are usually a dry period provided for the health of the cow. A mature dairy cow typically produces a calf every 12 to 14 months. Mature cows are replaced or culled from the herd at a rate of about 25% of a milking herd per year. Approximately 50% of new female calves

[30] R. Kersbergen, personal communication, Spring 2018.

are kept (sometimes sent elsewhere to be raised) for replacement, and reach the age of first calving at about 24 months, while the remaining excess calves are sold for veal or beef production(*CAFO Permit Guidance Appendix B: Animal Sector Descriptions*, 2003). Management-intensive rotational grazing (MIRG) is often considered an environmental best practice (Undersander et al., 1993). The financial budget for a typical dairy system is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide et al., 2004) and assumes a coupled dairy and hayfield farm with 66 cows. The values in the budget are per cow, rather than per acre. Table 29 summarizes the key revenues and costs for a typical Maine dairy cropping system.

Table 29. Dairy farm budget.

	Total	Per Cow	Per Cwt
Annual Revenue			
Number of Cows	66	-	-
Annual Milk Shipment (cwt)	10,413	157.77	-
Milk Receipts	$1,643,983,614	$18.08	$0.93
Crop and Hay Revenue	$42,266,367	$0.46	$0.02
Livestock Revenue	$90,905,490	$1.00	$0.05
Total Revenue	**$1,777,155,471.00**	**$19.55**	**$1.00**
Variable Costs			
Labor Expenses			
Family	$0	$0.00	$0.00
Hired	$112,710,312	$1.24	$0.06
Subtotal	*$112,710,312.00*	*$1.24*	*$0.06*
Purchased Feed Expenses			
Dairy Forage	$0	$0.00	$0.00
Dairy Concentrate	$440,928,072	$4.85	$0.25
Subtotal	*$440,928,072.00*	*$4.85*	*$0.25*
Livestock Expenses			
Breeding Fees	$20,524,023	$0.23	$0.01
Veterinary and Medicine	$43,745,013	$0.48	$0.02
Bedding	$24,595,506	$0.27	$0.01
DHIA Expenses	$7,591,077	$0.08	$0.00
Livestock Insurance	$15,473,718	$0.17	$0.01
Subtotal	*$111,929,337.00*	*$1.23*	*$0.06*
Crop and Pasture Expenses			
Seeds	$33,675,642	$0.37	$0.02
Chemicals	$24,887,070	$0.27	$0.01
Fertilizer	$23,408,424	$0.26	$0.01
Lime	$19,982,547	$0.22	$0.01
Other	$52,356,564	$0.58	$0.03
Subtotal	*$154,310,247.00*	*$1.70*	*$0.09*
Maintenance and Equipment Expenses			
Fuel and Oil	$61,457,526	$0.68	$0.03
Machinery Repairs	$124,810,218	$1.37	$0.07
Subtotal	*$186,267,744.00*	*$2.05*	*$0.10*
Deduction Expenses			
Milk Marketing	$15,057,198	$0.17	$0.01
Hauling and Trucking	$66,684,852	$0.73	$0.04
Subtotal	*$81,742,050.00*	*$0.90*	*$0.05*
Interest (5.4% on 1/2 of total operating expense)	$29,372,969.57	$0.32	$0.02
Total Variable Costs	**$1,117,260,731.57**	**$12.29**	**$0.63**

	Fixed Costs		
	Annual Overhead Expenses		
Property Tax	$81,939,897	$0.90	$0.05
Farm Insurance	$82,085,679	$0.90	$0.05
Dues and Professional Fees	$10,600,434	$0.12	$0.01
Utilities	$66,247,506	$0.73	$0.04
Miscellaneous	$155,632,698	$1.71	$0.09
Subtotal	$396,506,214.00	$4.36	$0.22
	Annual Depreciation and Interest Expenses		
Land	$84,147,453	$0.93	$0.05
Buildings	$268,009,794	$2.95	$0.15
Machinery and Equipment	$174,417,750	$1.92	$0.10
Subtotal	*$526,574,997.00*	*$5.79*	*$0.30*
	Livestock Herd Expenses		
Cows (Milking and Dry)	$108,753,372	$1.20	$0.06
Heifers	$45,890,091	$0.50	$0.03
Calves	$17,264,754	$0.19	$0.01
Dairy Bulls	$780,975	$0.01	$0.00
Subtotal	*$172,689,192.00*	*$1.90*	*$0.10*
Total Fixed Costs	**$1,095,770,403.00**	**$12.05**	**$0.62**
Total Annual Cost	**$2,213,031,134.57**	**$24.34**	**$1.25**
Net Farm Income (NFI)	**-$435,875,663.57**	**-$4.79**	**-$0.25**
Return over Variable Cost (ROVC)	**$659,894,739.43**	**$7.26**	**$0.37**

Hay

Hay is the most harvested crop in Maine by acreage. Grasslands are not a native ecosystem type in Maine, and without human intervention in the form of periodic mowing, early successional woody species including alders, birches, and poplars will invade, beginning the process through which the land will transition back to forest. It is possible that reversion of some hayfields to forest could be beneficial from an NCS standpoint. The financial budget for a typical hayfield cropping system is adapted from an enterprise budget prepared by the University of Maine Agricultural and Forestry Experimental Station (Hoshide et al., 2004) and assumes that 200 acres of hay is grown. Table 30 summarizes the key revenues and costs for a typical Maine hayfield cropping system.

Table 30. Conventional and coupled medium-large haylage.

	Total	Per Acre	PerTon
	Revenue		
Number of Acres	200		
Haylage Yield (tons)	1,200	6	
Price ($/ton)	$165.40		
Total Revenue	**$198480.00**	**$992.40**	**$165.40**
	Variable Costs		
Seeds	$0.00	$0	$0
Fertilizer	$8,607.51	$43.04	$7.17
Lime	$2,758.82	$13.79	$2.30
Chemicals	$0.00	$0.00	$0.00
Labor	$10,023.28	$50.12	$8.35
Diesel Fuel and Oil	$4,014.08	$20.07	$3.35

Maintenance and Upkeep	$4,062.36	$20.31	$3.39
Supplies	$2,758.82	$13.79	$2.30
Insurance	$91.04	$0.46	$0.08
Miscellaneous			
Rent or Lease	$3,448.52	$17.24	$2.87
Storage and Warehousing	$275.88	$1.38	$0.23
Other Expenses	$1,379.41	$6.90	$1.15
Interest	$736.60	$3.68	$0.61
Total Variable Costs	**$38,156**	**$190.78**	**$31.80**
Fixed Costs			
Depreciation and Interest	$24,410	$122.05	$20.34
Tax and Insurance	$1,944	$9.72	$1.62
Total Fixed Costs	**$26,354**	**$131.77**	**$21.96**
Total Annual Cost	**$64,510**	$322.55	**$53.76**
Net Farm Income (NFI)	**$133,970**	$669.85	**$111.64**
Return over Variable Cost (ROVC)	**$160,324**	$801.62	**$133.60**

Note. Numbers may not sum due to rounding.

Potato

Potatoes are second to hay in acres harvested in Maine. Growers selling to the processing market are generally under contract with the buyer, who can have considerable influence on which growing practices are employed. Growers for the processing market generally receive bonuses for potato size and quality, ability to store the crop until processing, and for highest yield.[31] Most growers are using a 2:1 rotation with one year of potatoes and two years of a much less valuable cash crop like a grain or an unharvested cover crop. Some growers are using a 3:1 rotation with a longer "off" period from potatoes or a more intensive 1:1 rotation.[32] Potato cropping involves key vulnerable periods with respect to potential soil erosion and loss of soil organic matter. Potatoes take about three weeks to emerge after planting, leaving the soil susceptible to erosion during this time.[33] Soils are also generally uncovered and susceptible after potato harvest, as well as following fall tillage in the preceding rotation crop.[34] The multiple tillage/cultivation passes inherent to potato planting and hilling are harmful for soil organic matter and aggregation (i.e., good soil structure), and despite the adoption of one-pass hilling by some growers, potato cropping systems remain by necessity tillage-intensive. Nurse cropping (Jemison, 2019), use of organic amendments (Mallory & Porter, 2007), and transition to longer rotations represent key opportunities to improve soil health in Maine potato cropping systems. The financial budget for a typical potato cropping system assumes the farm is 320 acres that grows 160 acres each of potatoes and barley in rotation.

Table 31 summarizes the key revenues and costs for a typical Maine potato cropping system.

[31] J. Jemison personal communication, February 2018.
[32] Daigneault et al., unpublished data, January 23, 2020.
[33] J. Jemison personal communication, February 2018.
[34] Daigneault et al., unpublished data, January 23, 2020.

Table 31. Potato farm budget.

	Revenue		
	Potato (cwt)	Barley (bu)	
Number of acres	160	160	
Yield/acre	310	53	
Yield	49,600	9,539	
Unit Price	$10.46	$3.87	
Annual Revenue	$318,816	$33,044.48	
	Total	Per Acre	Per Cwt
	Variable Costs		
Seed	$56,320	$179.57	$1.21
Fertilizer	$69,750	$142.29	$0.96
Lime	$4,884	$15.26	$0.10
Chemicals	$41,711	$130.35	$0.88
Labor	$86,950	$183.53	$1.24
Diesel Fuel and Oil	$19,486	$60.89	$0.41
Maintenance and Upkeep	$29,710	$92.84	$0.63
Supplies	$14,918	$46.62	$0.31
Insurance	$12,300	$38.44	$0.26
	Miscellaneous		
Utilities	$8,857	$27.68	$0.19
Custom Hire	$0	$0.00	$0.00
Rent or Lease	$16,553	$51.73	$0.35
Freight and Trucking	$3,930	$12.28	$0.08
Storage and Warehousing	$6,857	$21.43	$0.14
Other Expenses	$1,324	$4.14	$0.03
Interest	$8,900	$27.81	$0.19
Total Variable Costs	**$382,450**	**$1,034.86**	**$6.99**
	Fixed Costs		
Depreciation and Interest	$104,264	$325.82	$1.60
Tax and Insurance	$6,767	$21.15	$0.10
Total Fixed Costs	**$111,031**	**$346.97**	**$1.70**
Total Annual Cost	**$493,481.00**	**$3,084.26**	**$9.95**
Net Farm Income (NFI)	**$25,335.00**	**$158.34**	**$0.51**
Return over Variable Cost	**$136,366.00**	**$852.29**	**$2.75**

Note. Numbers may not sum due to rounding.

Diversified vegetable

The financial budget for a typical diversified vegetable cropping system assumes a 150-acre farm with 120 acres in woodlot, 10 acres in annual vegetable production, 10 acres in cover crops, and 10 acres in animal pasture. We assume that the farm grows beans, bell peppers, cucumbers, peas, pumpkins, sweet corn, squash, and tomatoes. This assumption is based on expert consultation and data from the 2017 USDA Census of Agriculture (2019). The crops are grown in five hundred 100-foot rows. Table summarizes the key revenues and costs for a typical Maine diversified vegetable cropping system.

Use of biochar is thought to be minimal in Maine at present,[35] but because diverse rotations that often include numerous field operations per season are common, there exist many opportunities to incorporate organic amendments including biochar into diversified vegetable systems. Use of mulches is common in these systems, and particularly in the case of organic mulch, represents an additional means of improving soil health (*Conservation Practice Standard: Mulching*, 2017). Conservation set-aside programs, where a portion of the land is put into conservation uses, are also feasible in these systems. Table 32 summarizes the key revenues and costs for a typical Maine wheat cropping system.

Table 32. Diversified vegetable farm budget.

Cost Component	Mean Veg (100-ft row)	Total Veg part of farm (500 rows)	Total/veg ac
Revenue	**$331.87**	**$174,233**	**$17,423.33**
Variable Costs	$135.31	$71,040	$7,104.01
Fixed Costs	$97.51	$51,194	$5,119.42
Mixed Veg Total Costs	**$232.83**	**$122,234**	**$12,223.43**
Return over variable costs	**$196.56**	**$103,193**	**$10,319.32**
Return over total costs	**$99.05**	**$51,999**	**$5,199.90**

Wheat

According to the 2017 USDA NASS Census of Agriculture, 262 acres of winter wheat were grown in Maine (2019). The financial budget for a typical wheat cropping system was adapted from an enterprise budget created by the University of Maine Cooperative Extension (Kary et al., 2011). We assume the farm is 90 acres and produces 45 acres each of wheat and straw. Table 33 summarizes the key revenues and costs for a typical Maine wheat cropping system.

Table 33. Wheat budget.

	Unit	**Unit/Acre**	**Revenue/Unit**	**Revenue/Acre**
		Revenue		
Wheat	bu.	45	$15.42	$693.88
Straw	sq. bale	45	$3.34	$150.34
Annual Revenue				**$844.21**
		Variable Costs		
		Material Expenses		
Wheat Seed	lb	120	$0.51	$61.68
Manure	ton	5	$12.85	$64.25
Chilean Nitrate	ton	0.05	$868.63	$43.43
Lime	ton	0.2	$20.56	$4.11
Subtotal				$168.75
		Miscellaneous Expenses		
Grain Drying	bu.	45	$0.34	$15.27
Leased Land	acre	0.25	$51.40	$12.85
Extra	%	5.00%	N/A	$14.99
Interest	%	4.73%	N/A	$8.60
Subtotal				$51.71

[35] S. O'Brian, unpublished data, Fall 2019.

Field Operation Expenses				
Primary Tillage	pass	1	$6.61	$6.61
Secondary Tillage	pass	2	$4.81	$9.62
Manure Spreading	pass	1	$23.91	$23.91
Fertilizer Spreading	pass	1	$3.14	$3.14
Lime Spreading	pass	0.2	$3.14	$0.63
Planting Wheat	pass	1	$5.54	$5.54
Combining	pass	1	$31.97	$31.97
Hauling Wheat	pass	1	$2.08	$2.08
Baling Straw	pass	1	$6.18	$6.18
Hauling Straw	pass	1	$2.05	$2.05
Subtotal				$91.71
Total Variable Costs				**$312.17**
Total Costs				**$312.17**
Net Revenue				**$532.04**

Natural Climate Solutions for Agriculture

Emissions factor estimates for agricultural NCS practices used in our model, accompanied by relevant citations and notes, are outlined in Table 34 and Table 35. Additional input assumptions that we applied for the dairy manure management practices are listed in Table 36. Information and literature reviews concerning NCS practices and their applicability to growing systems in Maine are contained in the following sections of text corresponding to each included NCS practice and cropping system.

Table 34. Baseline and NCS emissions factor reduction estimate for major crops applicable NCS practices.

	Crop	Emissions factor ($Mg\ CO_2e\ ac^{-1}\ yr^{-1}$)	Citation / Notes
Baseline values	Potato	2.11	Poore & Nemecek, 2018
	Lowbush blueberry	0.32	Percival & Dias, 2014
	Wheat	0.47	Adom et al., 2012
	Corn grown for silage	0.66	Adom et al., 2012
	Barley	0.47[36]	Adom et al., 2012
	Vegetables	2.21	Poore & Nemecek, 2018
	Apples	2.23	Poore & Nemecek, 2018; Karlsson, 2017
Reduction due to NCS practice application	Change to NT from intensive tillage	0.46	USDA COMET Planner (Swan et al., 2020)
	Change to NT from RT	0.36	USDA COMET Planner
	Change to RT from intensive tillage	0.10	USDA COMET Planner
	Use of cover crop (rye)	0.13	USDA COMET Planner
	Use of cover crop (red clover)	0.23	USDA COMET Planner
	Use of cover crop (oats and peas mix)	0.18	USDA COMET Planner
	Biochar application	1.6[37]	Ciborowski, 2019
	Amend with manure	0.16	USDA COMET Planner
	Convert to permanent perennial grass set-aside	1.29	Paustian et al., 2019
	Permanent riparian border on marginal land	1.69	National Council for Air and Stream Improvement & US Forest Service Northern Research Station, n.d.

[36] Assuming the same emissions for growing barley as a rotation crop as winter wheat for animal feed, due to similarities in equipment use and nitrogen fertility; Beegle, D. (2017).
[37] Assuming a one-time application of 5.9 Mg / ac with benefits for 20 years.

Table 35. Baseline and NCS emissions factor reduction estimates for dairy manure management practices.

	Manure management practice	Emissions factor (tCO_2e cow^{-1} yr^{-1})	Citations / Notes
Baseline value	One dairy cow	6.19	Maine DEP[38]
Reduction due to NCS practice application	Large (up to 2,500 cows) Complete Mix Anaerobic Digester with electricity generation	4.96	AgSTAR Livestock Anaerobic Digester Database (EPA, 2020), median value of applicable digesters located in northern states[39]
	Covered Lagoon/Holding Pond Anaerobic Digester	6.99	AgSTAR Livestock Anaerobic Digester Databas, mean of applicable digesters located in northern states
	Soild-liquid separation (SLS)	8.16	(ICF International, 2013)
	Small (300 cows) Complete Mix Anaerobic digester with electricity generation	4.96	AgSTAR Livestock Anaerobic Digester Database, median value of applicable digesters located in northern states
	Plug Flow Anaerobic digester with electricity generation	4.29	AgSTAR Livestock Anaerobic Digester Database, median value of applicable digesters located in northern states

[38] Unpublished data obtained through personal communication with Maine Department of Environmental Protection, July 2020.

[39] We included in this analysis data from any digester in a northern state using dairy manure as a primary animal / farm type, with size limited to digesters serving a maximum of 10,000 head of dairy cows. Northern states included CT, IA, ID, IL, IN, MA, ME, MI, MN, NE, MT, NY, OH, OR, PA, SD, VT, WA, WI, and WY. No data were available for ND, NH, NJ, and RI, which would otherwise have been considered applicable. Median values are reported in some cases to avoid biases in mean estimates resulting from skewed data distributions.

Table 36. Input assumptions for Maine dairy manure management practices. Estimates are based on data published in the EPA AgSTAR Database (EPA, 2020), ICF (2013), and USDA EQIP Cost Sheets (Maine Payment Schedules, 2020; USDA NRCS, 2014).

Estimate	Large complete mix anaerobic digester with electricity generation	Covered lagoon/holding pond anaerobic digester	Solid-liquid separation (SLS)	Small complete mix anaerobic digester with electricity generation	Plug flow anaerobic digester with electricity generation
Farm herd size (dairy cows)	2,500	300	1,000	300	300
GHG mitigated per farm (tCO_2e/yr)	16,000	2,097	8,162	1,920	2,883
GHG mitigated per cow (tCO_2e/head/yr)	4.96	6.99	8.16	4.96	4.29
Annualized Capital Costs ($/yr)	$96,564	$72,793	$34,894	$49,545	$75,983
Operations and Maintenance Cost ($/yr)	$158,136	$33,557	$27,309	$24,697	$37,877
Energy Sold ($/yr)	$177,848	$13,054	$0	$21,342	$21,342
Total Cost Less Energy ($ farm/yr)	$76,852	$93,296	$62,203	$52,901	$92,519
Total Cost Less Energy ($ cow/yr)	$31	$311	$62	$176	$308

No-till cropping (NT)

No-till cropping practices address the amount, orientation,[40] and distribution of crop and other plant residues on the soil surface year-round. Crops are planted and grown in narrow slots or tilled strips established in the untilled seedbed of the previous crop (*Residue and Tillage Management, No Till*, 2016). This practice includes maintaining most of the crop residue on the soil surface throughout the year and is commonly referred to as no-till. The common characteristic of this practice is that the only tillage performed is a very narrow strip prepared by coulters, sweeps, or similar devices attached to the front of the planter.

Benefits to soil include increasing organic matter, improving soil tilth, and increasing productivity as the constant supply of organic material left on the soil surface and in the soils as roots is decomposed by a healthy population of earthworms and other soil macro- and microorganisms. Operations and maintenance for this practice include evaluating the crop-residue cover and orientation for each crop to ensure the planned amounts, orientation, and benefits are being achieved. Weeds and other pests must be monitored to ensure pest populations do not exceed thresholds.

According to the 2017 USDA NASS Census of Agriculture, there were 21,676 acres of cropland in Maine reported to be implementing no-tillage practices, or 14% of all 152,796 acres of cropland in Maine that reported their tillage practices. For context, the USDA NASS Census of Agriculture found that Maine has a total of 472,508 acres of cropland, indicating that only 32% of the total crop area in the state reported any type of tilling practice (2019). As a result, additional inference may need to be made to allocate

[40] Orientation refers to the direction that crops are planted in a field, and can vary based on slope and direction.

tillage practices to the other 68% of cropland in the state, of which most could be no till (e.g., blueberries, hay, etc.).

Reduced-till cropping (RT)

Reduced-till practice manages the amount, orientation, and distribution of crop and other plant residues on the soil surface and in the soils as roots year-round while limiting the soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting (*Residue and Tillage Management, Reduced Till*, 2016). This practice includes tillage methods commonly referred to as mulch tillage where a majority of the soil surface is disturbed by non-inversion tillage operations such as vertical tillage, chiseling, and disking, and also includes tillage/planting systems with relatively minimal soil disturbance. Mulch tillage includes the uniform spreading of residue on the soil surface; planning the number, sequence, and timing of tillage operations to achieve the prescribed amount of surface residue needed; and using planting equipment designed to operate in high residue situations.

RT cropping practice improves soil health by increasing organic matter, improving soil tilth, and increasing productivity as the constant supply of organic material left on the soil surface and in the soil is decomposed by a healthy population of earthworms and other soil macro- and microorganisms. Operations and maintenance for this practice include evaluating the crop residue cover and orientation for each crop to ensure the planned amounts, orientation, and benefits are being achieved.

According to the 2017 USDA NASS Census of Agriculture, there were 31,953 acres of cropland in Maine reported to be implementing reduced-tillage (but not no-till) practices, or about 20% of farmed acres in Maine with reported tillage practices (2019).

Cover cropping

Cover cropping is growing a crop of grass, small grain, or legumes primarily for seasonal protection and soil improvement (*Cover Crop*, 2014). This practice is used to control erosion, add fertility and organic material to the soil, improve soil tilth, increase infiltration and aeration of the soil, and improve overall soil health. The practice is also used to increase populations of bees for pollination purposes. Cover and green manure crops have beneficial effects on water quantity and quality. Cover crops have a filtering effect on movement of sediment, pathogens, and dissolved and sediment-attached pollutants.

Operation and maintenance of cover crops include controlling weeds by mowing or by using other pest management techniques, and managing for the efficient use of soil moisture by selecting water-efficient plant species and terminating the cover crop before excessive transpiration. Use of the cover crop as a green manure crop to recycle nutrients will impact when to terminate the cover crop to match the timing of the release of nutrients from the decomposing biomass with uptake by the following cash crop.

Cover crops can generate a variety of benefits and costs, both internal and external to the farm. The net effect of these impacts on farm-level profitability is a function of many factors and in a given case may be either negative or positive, though appropriate selection of cover cropping design can dramatically reduce the likelihood of negative outcomes (Clark & Sustainable Agriculture Research & Education Program, 2007).

According to the 2017 USDA NASS Census of Agriculture, there were 55,462 acres of cropland in Maine reported to be implementing cover cropping, or 12% of all acres of cropland in Maine (2019).

Biochar Amendments

Biochar is a substance similar to charcoal that can be used as a soil or growing medium amendment. It is typically produced from biomass using pyrolysis technology where oxygen is either absent or depleted (Paustian, 2014). The pyrolysis process produces biochar as well as two additional materials, syngas and bio-oil, that may have commercial value as energy sources. Biochars differ depending on their feedstock (starting material), temperature, and residence time. A wide variety of feedstocks can be used depending on location, cost, and availability.

Biochars have utility as a tool for waste management and soil remediation. Biochars may also mitigate greenhouse gas (GHG) emissions through carbon sequestration. Biochar addition to agricultural soils has gained much recognition in the last decade because it can have positive effects on crop yield and soil nutrient stocks, among other parameters (Ding et al., 2016). It should be noted, however, that yield improvements are not universal, and based on current data, they are not expected in Maine's climate in major crops or systems including potato-grain (Jay et al., 2015), corn (Aller et al., 2018; Novak et al., 2019), orchards (Khorram et al., 2019; von Glisczynski et al., 2016), and vegetables (Jeffery et al., 2017).

A number of studies and reviews have highlighted the potential benefits of utilizing biochar as a soil amendment. These have covered issues such as mitigation of global warming through application of stable carbon into soil, waste management, bioenergy production, soil health, and productivity (Kookana et al., 2011). However, full lifecycle assessments that include the effects of biochar amendment on non-CO_2 trace gasses and soil nutrient fluxes are few (Gurwick et al., 2013) and not necessarily applicable to our growing system. Perhaps the most relevant estimate for our systems comes from a Minnesota Pollution Control Agency report, which used a literature review approach to account for direct and indirect nitrous oxide emissions, methane sink removals, soil organic carbon, and greenhouse gasses from field removal and transit, calculating that biochar amended soils at a one-time application rate of 15 t ha^{-1} would sequester 0.85 tC ha^{-1} $year^{-1}$.[41] This value is in line with prior literature, which indicates a broad range of sequestration values from 0.2 to 5.3 tC ha^{-1} $year^{-1}$ (Eagle et al., 2013; Woolf et al., 2010). While this Minnesota estimate represents a useful starting place for the present analysis, it should be stressed given the range of possible outcomes and number of variables that field studies conducted in local soils, using biochar from locally applicable feedstocks, are greatly needed to verify applicability of literature estimates to our system and provide additional data (Gurwick et al., 2013). The assumption of a one-time application with results annualized over 20 years is in line with how commercial-scale farmers might implement this practice in Maine.[42]

[41] P. Ciborwski, personal communication, June 16, 2020. This figure was not explicitly used in the analysis, but rather included in a range of estimates used to derive our mean annual sequestration rate of 1.6 tCO2e/ac/yr.
[42] J. Jemison, personal communication, Spring 2020.

Most studies using biochars as soil amendments show that biochar can increase soil productivity, but some show decreased productivity (Maguire & Agblevor, 2010). This is likely due to the wide variety of biochars that can be produced and the variability among soils and cropping systems. Biochar can increase soil productivity through the application of nutrients (for some biochars and some nutrients), a liming effect for alkaline biochars, and through improvements in soil properties that include aeration, moisture retention, and improved soil structure. Most minerals present in the feedstock are concentrated in the biochars produced, but much of the nitrogen and sulfur is lost during pyrolysis. Therefore, supplemental nitrogen will generally be needed when using biochars as a soil amendment. Wood biochars, for which locally available feedstock is abundant in Maine, often have particularly low nutrient concentrations.

Biochar can be applied by hand or by using widely available equipment including broadcast seeders and lime or manure spreaders at larger scales. To increase efficiency by limiting the number of field operations needed, biochar can be mixed with other amendments including lime and liquid manure prior to application. Biochar can be applied as a topdress amendment, broadcast and incorporated through subsequent tillage, or applied in surface or sub-surface bands. A potential tradeoff to consider is that biochar, especially when surface-applied in no-till or reduced-tillage systems, can bind to herbicides and diminish their efficacy (Major, 2010). Additional research is needed to suggest tailored application rates most applicable to growing contexts in Maine.

It is unknown how many farmers in Maine are currently incorporating biochar into their farm systems. There is no centralized reporting system for biochar use, and some farmers produce their own biochar from their woodlots. However, the overall figure for Maine at this time is likely to be very small.

Manure Management

Large dairy and hog farms with manure lagoons emit significant amounts of methane (CH_4), a potent greenhouse gas that can be mitigated through a suite of practices including changes to agricultural land management. Manure management—how manure is captured, stored, treated, and used—has important implications for farm productivity and the environment (*Manure Management*, 2020). For context, about 88% of CH_4 emissions from livestock manure management in the US are generated from dairy (56%) and swine farms (32%) (*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2017, Chapter 5, Table 5-6*, 2019). When applied according to the agronomic needs of crops, manure can improve productivity by reducing the need for commercial fertilizer while enhancing soil health. Manure management can also affect water quality primarily by leaching nutrients (e.g., nitrogen and phosphorus) to groundwater and creating runoff resulting in eutrophication.

A single dairy cow weighs approximately 1,400 lbs and produces approximately 80 lbs of recoverable manure per day per 1,000 lbs of animal unit (*Animal Manure Management*, 1995), which works out to 112 lbs of recoverable manure per dairy cow per day. This translates to 40,880 lbs, or 18.5 metric tons, of manure produced per cow on an annual basis. On average, dairy manure produces about 0.023 m^3 of methane per kilogram of manure (0.37 ft^3 per lb) on a wet basis (Aguirre-Villegas et al., 2016), which translates to 15,126 ft^3 of methane per cow per year, or approximately 6 lbs of CO_2-equivalent per year.

Most methane associated with manure is emitted during storage (Fangueiro et al., 2008). Maine farmers must store manure over the winter months because they are prohibited from spreading manure at that time (Winter Spreading of Manure, 2003). There are a number of manure management practices that can be employed to mitigate GHG emissions. These include placing impermeable covers on lagoons and liquid/slurry ponds; adding a solids separator to lagoon systems, which can reduce emissions by 19% or more (Aguirre-Villegas et al., 2016; Fangueiro et al., 2008); and adopting an anaerobic digester system (e.g., a covered lagoon, complete mix, or plug flow system), which can reduce emissions by approximately 60% (Aguirre-Villegas et al., 2016; Amon, Kryvoruchko, Amon, et al., 2006; Amon, Kryvoruchko, Moitzi, et al., 2006). Farmers who install an anaerobic digester on their livestock operations can use manure to produce a biogas that can be burned to generate electricity. Digesters can also reduce greenhouse gas emissions from manure storage and handling. The size of the digester will vary by the area being managed and can range from farm- to community-scale. For example, Summit Energy announced in May 2019 that they will construct a $20 million digester in Clinton, Maine, that will utilize waste from five dairy farms that make up 17% of the state's dairy production, and the company claims this will generate about 125,000 MMBtu of gas per year (Summit Utilities Inc., 2019).

To our knowledge, only one Maine dairy farm currently utilizes an anaerobic digester for manure management: the Fogler Dairy Farm in Exeter (*Stonyvale Farm (Fogler Farm) Anaeorobic Digester System*). Other mitigation systems have varying applicability in Maine depending on the size of the herd, which has implications for installment costs, and on the challenges posed by Maine's cold climate (ICF International, 2013). For example, freezing temperatures can impair the functioning of solids separators or inhibit the production of methane in digesters.

Manure Amendments

Manure, when used as a soil amendment, can act as a fertilizer and can also improve the physical qualities of the soil including tilth, water infiltration and retention, and soil porosity (Risse et al., 2006). Most of these physical improvements are linked to an increase in soil organic matter. The addition of manure to soil can increase carbon sequestration (Koga & Tsuji, 2009), but it also increases emissions of nitrous oxide (a potent greenhouse gas), especially when it is injected into soils rather than broadcast (Adair et al., 2019; Dittmer, 2018; Duncan et al., 2017). Increased carbon sequestration due to manure application may be offset by increased nitrous oxide emissions, at least on a global aggregate scale (Zhou et al., 2017). Thus, the environmental benefits of manure as a soil amendment may not include a reduction in greenhouse gas emissions. Nonetheless, the potential for manure amendment to reduce dependency on chemical fertilizers, use of a byproduct of animal production that would otherwise be considered waste, and increased climate resilience through improvements to soil health are important benefits from this practice that warrant consideration.

Manure amendment can help supply crop nutrient demand, but its nutrient composition varies (Brown, 2015; Chastain & Camberato, 2003). The average proportion of nitrogen-phosphorus-potassium in dairy manure is 11, 7, and 9 lbs per ton on a dry matter basis (Wilson, 2020). In general, plants require much more nitrogen than either phosphorus or potassium, and so applying manure to meet plant nitrogen needs will oversupply phosphorus and sometimes potassium. Further, most nitrogen in manure is stored in organic forms that are not plant-available and must be converted to inorganic forms through microbial processes influenced by the carbon:nitrogen ratio of the manure. The resulting variable rate of nutrient release complicates the timing of manure application to coincide with plant fertility needs. The composition of the manure, nutritional demands of the crop, and the nutrient content and cropping history of the soil are all important considerations in determining amendment rates (Beegle, 2017; Koehler, 2020). Overapplication of fertilizers can result in negative consequences for water (Wilson, 2020) and air quality (Duncan et al., 2017).

Manure application methods vary depending on the liquid content of the manure. Both solid and liquid manure can be broadcast onto the surface of a field (and may be incorporated), while liquid manure can be injected (Rausch & Tyson, 2019; University of Minnesota Extension, 2018). Broadcasting solid or semi-solid manure with a spreader is the oldest and simplest method of application. Liquid manure is applied using liquid manure tankers pulled behind a tractor or mounted on a truck. Liquid manure can also be broadcast using irrigation equipment, either by sprinkler irrigation or by a drag-hose, tractor-mounted irrigation system (Rausch & Tyson, 2019). A drawback to the broadcasting method is the potential loss of inorganic and plant-available nitrogen to volatilization. This loss can be mitigated by incorporating the manure into the soil. Manure can be incorporated immediately upon broadcast or within a few days; the more quickly it is incorporated, the less ammonia is released to the atmosphere.

The injection method for liquid manure was developed to reduce odors and other issues related to the release of ammonia following the broadcasting of manure. It is also compatible with no-till systems. There are three injection methods: knife injection, in which vertical blades create 6-8" vertical grooves that collect manure; sweep injection, which places a broad, horizontal band of manure underneath the surface soil; and disk or coulter injection, which uses a rolling disk or a coulter to create a vertical groove that collects manure (University of Minnesota Extension, 2018). Injection of manure greatly reduces ammonia volatilization, in some cases by nearly 100%, but it can increase nitrous oxide emissions by up to 152% (Dittmer, 2018; Zhou et al., 2017) and additionally result in increased nitrous oxide fluxes during winter freeze-thaw events (Adair et al., 2019).

Three factors that influence the cost of manure management are loading, transporting, and application. Each may require specialized equipment and have its own constraints. For example, loading is constrained to time periods when animals are not present (except in the case of an external storage structure). Transportation costs are influenced by the distance traveled, hauling capacity, and travel speed. Application is constrained by soil and plant conditions and requires specialized equipment (University of Minnesota Extension, 2018).

Manure may be stored, transported, and applied in three forms: solid, liquid and slurry. Solid manure is cheaper to transport due to its lower water content, and therefore can be transported farther. Liquid and slurry manure have the lowest loading costs, but they have high transport costs. Liquid manure, despite its high transport cost, is the cheapest to apply, especially when existing irrigation equipment is modified to broadcast manure (Massey & Payne, 2019). In general, manure is expensive to transport, especially when it has a high liquid content; thus there are important economic tradeoffs between type of manure and hauling distance (Harrigan, 2001, 2011; Risse et al., 2006). A study of manure application in New York suggested that on average, farms were able to apply just under 240,000 gallons of liquid manure in a 10-hour day to fields that were on average 3.5 miles away. On average, about 15,000 gallons of manure were spread per application hour—approximately the amount required to supply one acre of corn with its total nitrogen needs for the growing season, if the manure is incorporated. On average, the estimated total annual cost of manure application was $105,000, or about $134 per cow (Howland & Karszes, 2012). Because it requires specialized equipment and more time to apply, injection is somewhat costlier than broadcasting (Hanchar, 2014), though one study indicated it only increased the cost by about 6% compared to broadcast application plus incorporation (Hadrich et al., 2010).

Crop and Grassland Conservation

Marginal cropland and pasture is often not profitable to farm in many years. As such, some farmers voluntarily retire cropland utilizing rental payments or easements. For example, the national Conservation Reserve Program (CRP) provides a yearly rental payment if farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality (Farm Service Agency, 2019). Contracts for land enrolled in the CRP are typically 10-15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and enhance wildlife habitat. Changes in vegetation and reduced soil disturbance are also likely to increase carbon sequestration and/or reduce GHG emissions as land is taken out of production.

According to the USDA, there were 7,744 acres in Maine enrolled in the Conservation Reserve Program as of September 30, 2017 (Farm Service Agency, 2017). These lands received a mean rental payment of $38/acre/yr for cropland and $18/acre/yr for grassland (Farm Service Agency, 2018). These values are relatively low compared to other parts of the US, indicating that there are limited opportunity costs of setting aside marginal land in Maine.

Additionally, the 2017 USDA Census of Agriculture reported that 484 farms in Maine had a conservation easement totaling 36,274 acres (2019).

Riparian Buffer

Riparian buffers are vegetated areas adjacent to streams that differ from their surrounding land practices (i.e. agriculture or forest land). In agricultural lands, installation of riparian buffers usually involves planting trees, shrubs, and grasses 35 to 100 feet away from the stream boundary. Most literature suggests a three-stage approach to planting buffers (Dybala et al., 2019). The first zone closest to the stream should consist of large woody trees and shrubs that have traditionally coevolved with streams to withstand flooding. This zone provides aquatic shade, streambank stability, and dead wood and leaf litter nutrients for the stream. Zone 2 filters runoff and absorbs waterborne pathogens and nutrients. It has similar vegetation to Zone 1 as it also consists of trees and shrubs. This zone can have larger trees with smaller trees and shrubs beneath. This zone can also be used for commercial harvest of non-traditional agricultural and commercial species like Christmas trees, nut crops, shade-loving wildflowers, ginseng, red oak, and sugar maple. Zone 3 filters water and slows down runoff. This zone consists of tall grasses and is the last zone adjacent to working cropland and pastureland.

Riparian buffers in agricultural land have large potential benefits for landowners and downstream communities. Riparian zones have a relatively large carbon sequestration potential that can also offset emissions from traditional agricultural practices. Furthermore, they filter nutrients and collect sediments, which can improve water quality (Zhang et al., 2010). Riparian buffers can also provide local habitat and biodiversity benefits.

Key costs to implementing riparian buffers include planting, maintenance, and opportunity costs. Agricultural land directly adjacent to waterways is often less productive than the landowner's average farmland, so the opportunity cost of retiring crop land is typically lower in buffer zones relative to the most productive areas of the farm (A. J. Daigneault et al., 2017). There is estimated to be approximately 21,000 acres of potential riparian buffer zone land in Maine agriculture (Cook-Patton et al., 2020). The costs of implementing riparian buffers in Maine are listed in Table 37.

Table 37. Detailed riparian buffer costs.

Item	Min	Med	Max
Establishment Costs ($/ac)			
First 2/3 Stages of Trees and Shrubs, tree dominated buffer. Assumed 80% trees, 20% shrubs.			
Tree Saplings:	$386.49	$463.78	$541.08
Shrub Saplings:	$91.67	$110.00	$128.33
Tree Labor + Mats + Shelters:	$297.30	$356.76	$416.22
Shrub Labor + Mats + Shelters:	$61.94	$74.32	$86.71
Tree Shelter + Mats:	$594.59	$713.51	$832.43
Shrub Mats:	$61.94	$74.32	$86.71
Shipping and handling for tree mats and shelters:	$49.55	$59.46	$69.37
Shipping and handling for shrub mats:	$4.95	$5.95	$6.94
Total Stage 1 and 2 Establishment Cost:	$1,548.42	$1,858.11	$2,167.79
3rd stage, grasses			
Planting	$5.23	$42.23	$79.24
Seeds	$52.30	$204.44	$356.58
Site Preparation	$9.41	$36.40	$63.39
Fertilizer/Lime	$15.69	$47.46	$79.24
Mowing or Herbicide	$5.23	$50.16	$95.09
Total Stage 3 Establishment Cost:	$87.86	$380.70	$673.53
Total Establishment Cost			
Stage 1, 2, and 3 Establishment Cost:	$1,636.28	$2,238.81	$2,841.33
Maintenance Costs ($/ac)			
Replanting (assuming 80% survival rate)	$58.57	$81.58	$104.60
Stage 1 & 2 Mowing and/or Herbicide	$39.64	$79.28	$118.92
Stage 3 Mowing	$6.28	$18.83	$31.38
Stage 1, 2, and 3 Maintenance Cost:	$104.49	$179.69	$254.89
Total Riparian Buffer Costs and Benefits			
Total Riparian Buffer Cost ($/ac)	$1,740.77	$2,418.50	$3,096.22
Annualized Costs over 20 years ($/ac/yr)*	$139.68	$194.07	$248.45
Annual Average Carbon Sequestration (tCO_2e/ac/yr)	1.23	1.69	2.13
Break Even Carbon Price ($/$tCO_2e$)	$114	$115	$117

*costs annualized over 20 years using a discount rate of 5%

Table 38 summarizes the range of agricultural NCS GHG mitigation factors from the literature. This study used the median (medium) values to quantify the impacts of implementing each practice.

Table 38. Range of agricultural NCS GHG mitigation factors from literature ($tCO_2e/ac/yr$).*

NCS Practice	Min	Median*	Max
No-till from Intensive	0.01	0.46	0.89
No-till from Reduced	0.00	0.36	0.70
Reduced tillage	0.00	0.10	0.19
Cover Crops	-0.15	0.18	1.06
Biochar	1.10	1.60	2.82
Amend w/ Manure	-0.13	0.16	0.60
Convert to Perennial	0.65	2.31	3.47
Riparian Buffer	1.74	2.20	2.64
Dairy Manure Management	1.94	4.73	6.68

**only median (medium) values were used for this analysis*

Appendix C. Statewide Extrapolation of Forest Carbon Estimates

To incorporate the potential additive effects of the current forest carbon stock and future forest growth in areas outside our project study area we used U.S. Forest Service Inventory and Analysis plot data to estimate (1) live forest carbon ca. 2010, and (2) average 10-year change in forest carbon. The live forest carbon ca. 2010 was 177 MMTC and the average 10-year change was 23.6 MMTC/yr based on all ~1,700 plots outside our project study area. We added these values to the simulated predictions for our study area to derive a statewide estimate of total aboveground forest carbon from 2010 to 2070 (Figure 29). It is important to note that this process implicitly assumes no change in forest management on commercial forestlands outside our project study area, and it does not account for the potential effects of climate change on forest productivity.

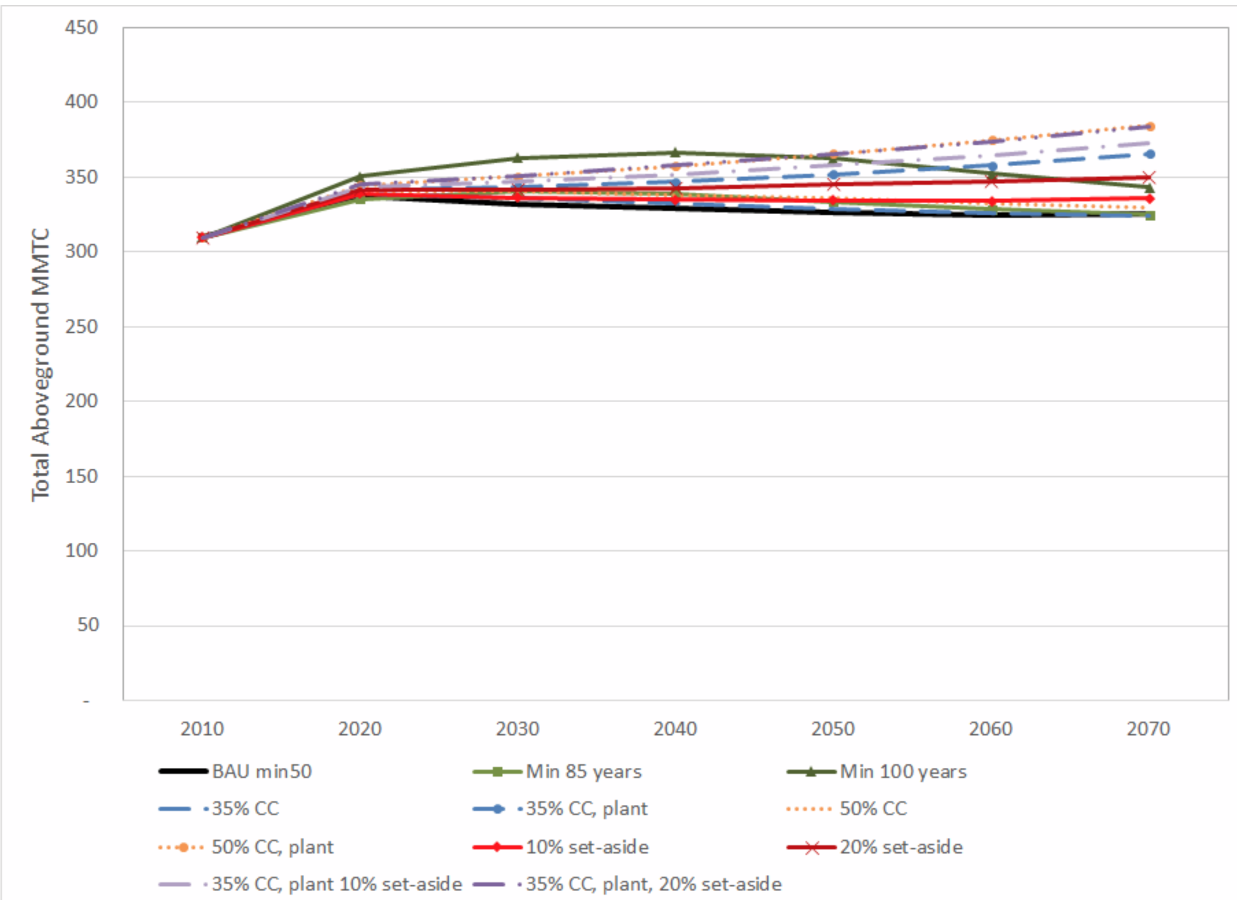


Figure 29. Total forest carbon stock (MMTC) for all of Maine, including 7.5 million acres outside of the Landis model study area, modeled from 2010 to 2070.

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