Interim Report

# Maine Forestry and Agriculture Natural Climate Solutions Mitigation Potential


Adam Daigneault

Erin Simons-Legaard

Sonja Birthisel

Jen Carroll

Ivan Fernandez

Aaron Weiskittel

**University of Maine**


**August 2020**

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Center for Research on Sustainable Forests

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# Executive Summary

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions by 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. To achieve climate goals, we must also look for ways to remove carbon from the atmosphere (i.e., negative emissions) and sequester it in soils. Natural climate solutions (NCS), such as cropland nutrient management, planting trees, and conservation, that sequester carbon or limit GHG emissions can affect near-term GHG mitigation goals in cost- effective ways and enhance long-term 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 is 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. This was done by modeling a 'baseline' or 'business as usual' (BAU) pathway, to which all other scenarios or pathways were compared or measured against. Next, a list of potential NCS practices that could feasibly be implemented in Maine was established by a mix of expert input and data availability. Finally, an estimate of the 'cost' and 'effectiveness' of implementing the NCS practices under consideration was determined.

Maine's forests currently sequester nearly 70% of the state's annual gross greenhouse gas emissions and continued 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, it was determined that most forest management NCS practices can be implemented at a cost of $10-20 per ton carbon dioxide equivalent ($tCO_2e$), which is relatively inexpensive compared to most non-NCS opportunities (Table ES1). Increasing the intensity of active forest management could yield about 4.5 million $tCO_2e$/yr for this study area in additional carbon sequestration at a cost of $64 million/yr or $14/$tCO_2e$, which was significantly more effective than increasing rotation lengths. All scenarios tested have minimal potential leakage, while additional ecosystem services benefits were realized with some of the scenarios.

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 786,000 $tCO_2e$/yr in GHG emissions or about double the sector's current annual emissions (Figure ES1). This combined approach for the agricultural sector is estimated to cost $26.3 million/yr or $34/$tCO_2e$. Consequently, setting aside the issue of uncertainties, this analysis showed that Maine's agricultural sector has the potential to reduce its within-sector emissions or even be net-negative as a sector.

Although the analysis has some important limitations that will be refined in future efforts, this work represents a critical first step for exploring the potential benefits of incorporating NCS in Maine's climate action implementation. Currently, interviews and focus groups are being used to explore the potential technical, financial, social, and/or policy barriers and opportunities that stakeholders face in implementing the NCS practices. These findings will be incorporated into future modeling efforts and annual progress reports.

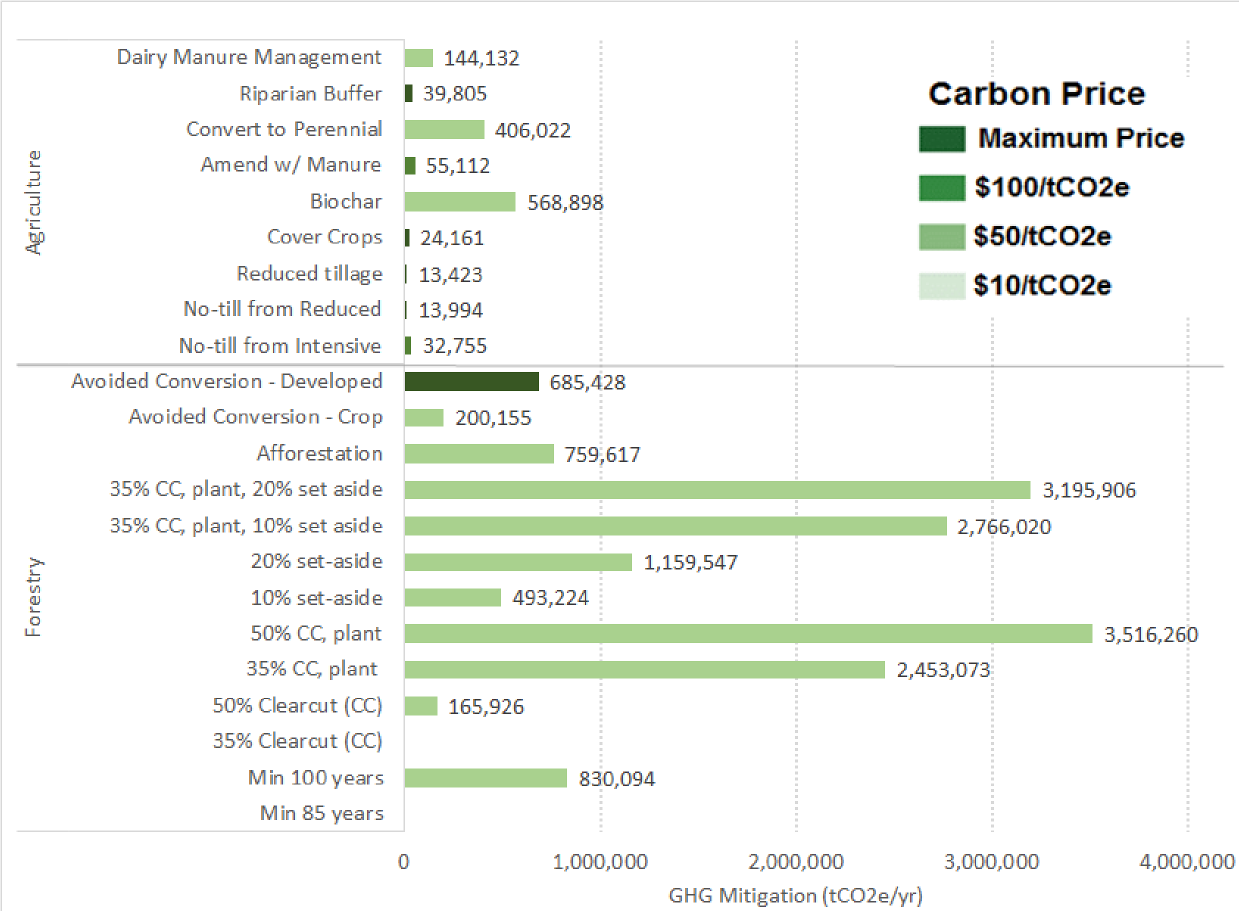


*Figure ES1. Summary of Maine NCS mitigation potential (tCO2e/yr) and break-even carbon price ($/tCO2e)*

# 1. Introduction

The State of Maine has recently set a goal to reduce gross greenhouse gas (GHG) emissions by 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 (An Act To Establish the Maine Climate Change Council To Assist Maine To Mitigate, Prepare for and Adapt to Climate Change, 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). Furthermore, it is uncertain how many additional mitigation measures could be taken to help reduce Maine's GHG emissions, nor what it might cost to implement these practices.

Maine's GHG reduction goals reflect the evidence of current and potential future harmful impacts climate change could have on the state's people and ecosystems. Milder winters and earlier springs will 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 coastal communities. However, Maine's terrestrial environment is also being strongly influenced by changing climatic conditions that are likely to place increasing stress on Maine's forests, particularly those species that are either at their northern or southern limit, or 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 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. Of importance for Maine, rural communities have limited economic resilience because of a lack of redundancy in infrastructure and 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 (i.e., negative emissions) and sequester it in soils. 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, NCS have the potential to mitigate 21% of 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 better 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 and enhance effective implementation of NCS practices. To date, most NCS studies are global and national-scale, and state-level estimates are often reliant on assumptions more applicable elsewhere. The practices covered are also often typical of more conventional forestry or agricultural systems. Moreover, Maine foresters and farmers may face unique implementation barriers important in the state, but 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,*** to achieve this a model 'baseline' or 'business as usual' (BAU) pathway was established that all other scenarios or pathways will be compared to or measured against. In this case, we assumed a continuance of current policy and practices that essentially maintain the harvest, cultivation, and planting rates that have been apparent over the past decade. ***Second***, we needed to define 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 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 through a mix of expert input and data availability.

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 a number of costs and benefits relative to the baseline or BAU. Key benefits could include reduced GHGs or increased carbon sequestration, yield improvements, cost-savings from reduced expenditures, and other environmental benefits such as improved soil health and water quality (Figure 1). 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 1. Key costs and benefits of implementing natural climate solutions relative to business as usual.*

Figure 2 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 to provide 0.10 metric tons of carbon dioxide equivalent ($tCO_2e$) per year of additional carbon sequestration, equating to just over 5,000 $tCO_2$/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 less input costs) 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.

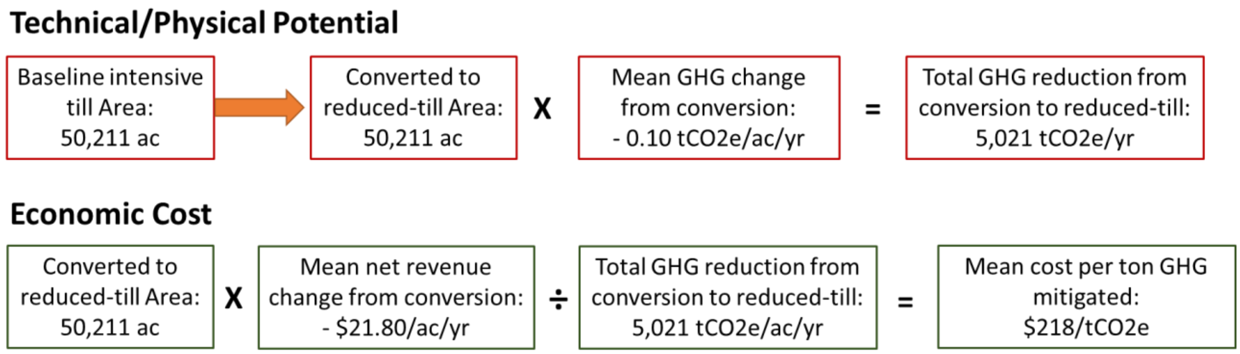


*Figure 2. Example of how to calculate biophysical potential and economic cost of converting all eligible Maine potato farms from intensive to reduced crop tillage.*

## 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, multi-faceted, and provides about $8 billion/yr in direct economic impact. Furthermore, Maine's forests currently sequester nearly 70% of the state's annual gross greenhouse gas emissions (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 3). However, significant changes to both natural forest and industry are expected in the decades to come via shifts in market demand, policy adjustments, and climate change. Furthermore, Maine's forest is a transitional ecotone with a broad mixture of species, which means that changing climatic conditions create significant stress as most species are either at their northern or southern limit. As a result, we seek to analyze the potential impacts on Maine's forest carbon sequestration through 2100 under a range of different management regimes. Furthermore, we evaluate the impact of our assumptions via sensitivity analysis. This section provides an overview of how the modeling of forest natural climate solutions was conducted.

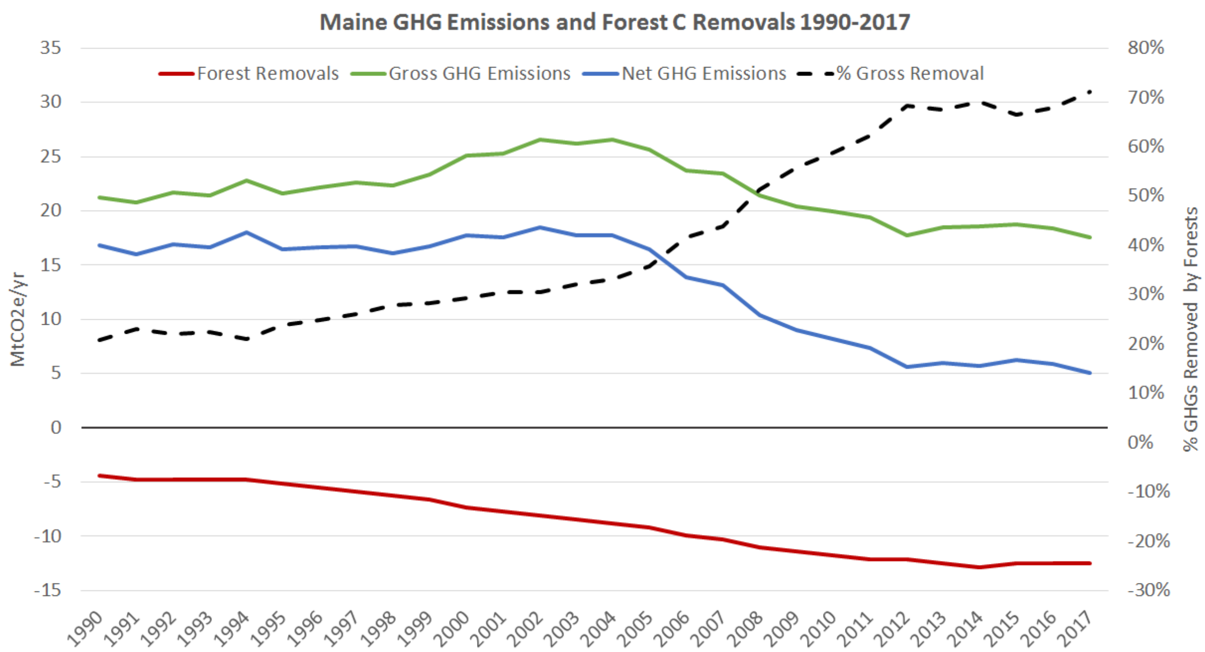


*Figure 3. Maine GHG emissions and forest carbon removals, 1990-2017 (Source: Domke et al., 2020; Maine DEP, 2020).*

### 2.2.2 Forest NCS Practices/Scenarios

We modeled a number of different forest practices with NCS potential that varied the approach to forest management and use on the nine million acre case study block of land in Maine. We established seven scenario foci with many including more than one set of scenarios within each focus (Table 1). These were:

1. Extended Rotation: increased minimum stand age eligible for harvest from BAU 50 year to 85 or 100 years.
2. Clearcut/Partial harvest distribution: increased % of the area harvested by clearcut (from 10% to 35% or 50%). Wood supply was held constant by proportionally reducing overall harvest footprint, assuming on average 1 acre of clearcut would result in the same volume harvested as 2 acres of partial harvest.
3. Planting: added planting (or artificial regeneration) after clearcut with a 700 tree per acre mix of red and white spruce.
4. Set-aside: Reserved 10% or 20% of forestland, which was permanently removed from harvest.
5. Triad approach: Mix of BAU rotations, clearcuts with planting, and permanent set-asides.
6. Avoided Forest Conversion: Held 2010 forest area constant via renting land at cost of highest and best use if converted.
7. Afforestation: Plant trees in eligible areas not forested since at least 1990.

Impacts to aboveground carbon, harvested wood carbon, revenues, and costs were estimated using a mixed modeling approach, with most of the scenarios conducted with Landis, a landscape-level dynamic forest ecosystem model.

*Table 1. Forest NCS Practices modeled with and without Landis-II.*

| Scenario Focus | Scenario Name | % Clearcut | Min. Stand Age | Plant after Clearcut | % Land Set aside |
|---|---|---|---|---|---|
| | | *Landis-based Scenarios* | | | |
| Baseline/BAU | BAU age (min 50) | 10 | 50 | no | 0 |
| Extended | Min 85 years | 10 | 85 | no | 0 |
| Rotation | Min 100 years | 10 | 100 | no | 0 |
| Clearcut/Partial | 35% Clearcut (CC) | 35 | 50 | no | 0 |
| Harvest Dist. | 50% CC | 50 | 50 | no | 0 |
| Clearcut & Plant | 35% CC, plant | 50 | 50 | yes | 0 |
| | 50% CC, plant | 50 | 50 | yes | 0 |
| Set-aside forest | 10% set-aside | 10 | 50 | no | 10 |
| land | 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 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; David J. 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 (D. J. Mladenoff et al., 1996; D. J. 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 (homogenous 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 2070. 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 plot data and Landsat satellite imagery.[1] Our study area (Figure 4) encompassed approximately 9 million acres of primarily commercial forestland. Owners within this area are predominantly considered large (>10,000 acres) land owners and represent a diverse range of ownership types (e.g., Family, Timber Investment Management Organizations, Real Estate Investment Trusts, and Non-profit Organizations).

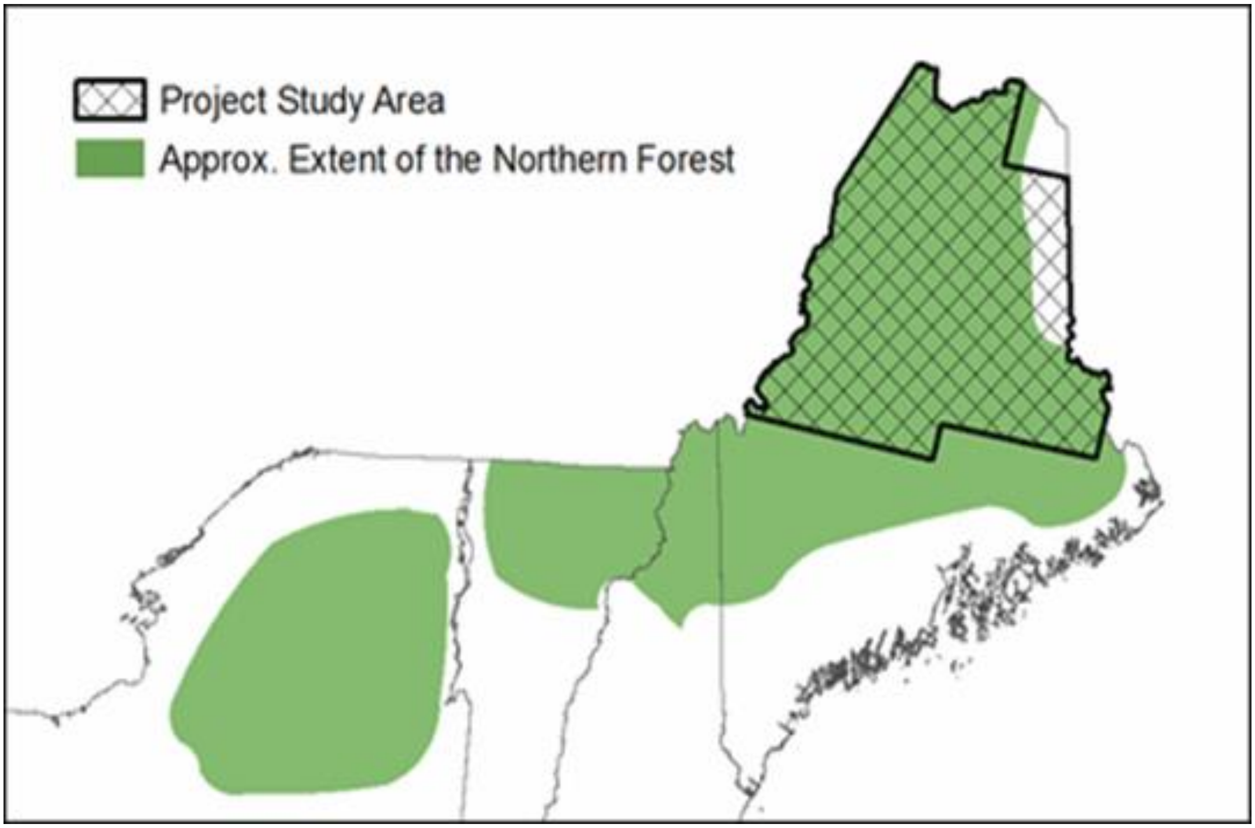


*Figure 4. Project study area for forest landscape projections using LANDIS-II encompassed approx. 9.1 million acres of predominantly commercial forestland in northern Maine.*

The LANDIS-II model comprises 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 (Fargione et al., 2018) to model timber harvesting. We modeled two harvest prescriptions: clearcut and partial harvest. Partial harvests were designed to remove an average of 50% of the live biomass from a stand. Biomass removal was variable, representing a combination of complete overstory removal within harvester trails and uniform selection in the remainder of the selected stand. Our baseline or Business-as-Usual (BAU) scenario emulated the average cumulative harvest rate within the study area, as estimated from a Landsat-derived time series

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

of forest disturbance (2000-2010) (K. R. Legaard, 2018). The BAU scenario (hereafter referred to as BAU min50) set the minimum stand age eligible for harvest as 50 years old, which follows historical trends for Maine timber harvests.

Annual net primary productivity (ANPP) is a key parameter in the modeling of forest growth and succession within LANDIS-II. We used the process-based PnET-II model (Aber et al., 1995) to estimate ANPP for each species in a manner similar to previous LANDIS-II studies (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 (2020-2070) ANPP 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 scenario (RCP 2.6) and obtained from the USGS Geo Data Portal (*USGS Geo Data Portal*, 2020).

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 based on the results calculated total aboveground carbon at each interval 2010-2070 for each forest management scenario. In addition, for demonstration purposes we compared the status of a variety of ecosystem services ca. 2060 under a subset of the management scenarios relative to our baseline. We included spruce-fir carbon, late successional forest (>100 years old) for both spruce-fir forest (>75% balsam fir, spruce sp. relative abundance) and northern hardwood (>75% sugar maple, yellow birch, American beech relative abundance), as well as lynx foraging habitat (regenerating forest <40 years old with >50% spruce-fir relative abundance).

### 2.2.4 Non-Landis 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 of marginal non-forest land with trees, and b) avoided conversion of current forestland that is considered under threat of being changed into developed or agricultural use.

The afforestation (or forest restoration) estimates were derived based on methods from Cook-Patton et al. (2020), which evaluated the potential for the contiguous U.S. at a high spatial resolution. Locations were initially constrained to areas where forests with ≥ 25% tree cover historically occurred. Additional assumptions excluded all cropland not located in areas with challenging soil conditions[2], 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 primarily be via natural regeneration and include a mix of tree species already growing in Maine. Annual

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[2] 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/).

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 (i.e., deforestation) estimates were derived from methods similar to Fargione et al. (2018). Future conversion was based on extrapolating historical trends forward, following the New England Landscape Futures (NELF) (*New England Landscape Futures Explorer*, n.d.) baseline projections. According to NELF, approximately 8,500 acres of land are estimated to be converted to development or agricultural land in Maine each year, with 76% of the conversion going to development (Figure 5. Projected cumulative Maine land cover change, 2010 to 2060. (Source: NELF, 2020)). Costs of mitigation included opportunity costs of land sale, using the same sources as the afforestation estimates. Carbon sequestration estimates were based on an 'average' Maine stand in FIA, and assumed to accumulate at a mean rate of 3.1 $tCO_2e$/ac/yr. That is, 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.

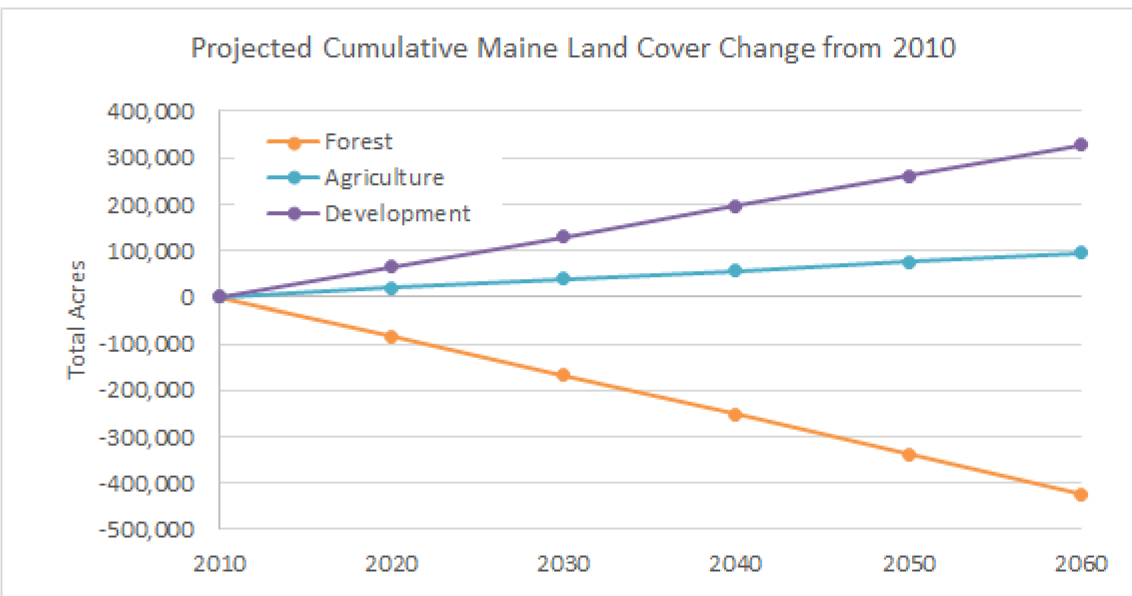


*Figure 5. Projected cumulative Maine land cover change, 2010 to 2060. (Source: NELF, 2020)*

### 2.2.5 Forest Carbon and Cost Estimation

As discussed above, forest carbon sequestration 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 carbon in harvested wood products and landfills over time. The harvested wood product and landfill estimates were derived using the methods from Smith et al. (2006), and were roughly equivalent to 20% of the total biomass/carbon removed/harvested from the stand (Bai et al., 2020). The remaining harvested carbon was assumed to be emitted immediately, either through combustion for energy or otherwise (Smith et al., 2006). Total carbon sequestration in any given year was the sum of aboveground forest carbon and harvested wood 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 (*Annual Stumpage Price Reports*, 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 on 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). In addition, we conducted additional sensitivity analysis 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 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). A bulk of the emissions are from livestock (via enteric fermentation and manure management), with dairy contributing 48% of the total agricultural sector emissions (Figure 6). Agriculture, excluding forestry, fishing, and aquaculture, encompasses 1.3 million acres (*2017 Census of Agriculture*, 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, 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

(*2017 Census of Agriculture*, 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.

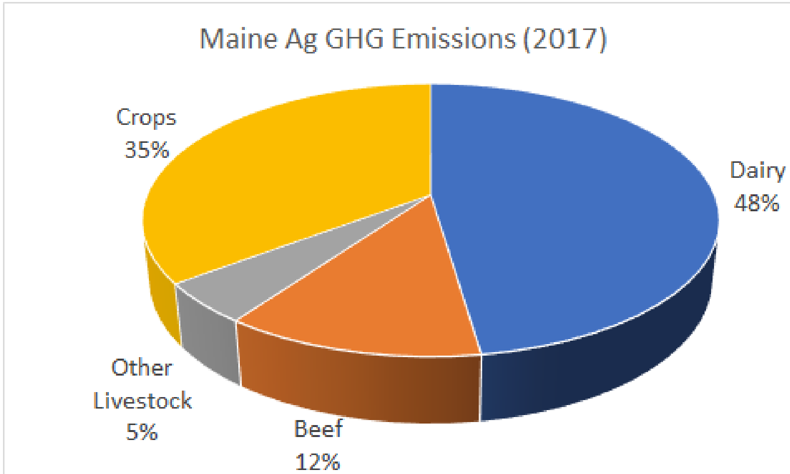


*Figure 6. Maine Agricultural GHG Emissions by major enterprise (source: DEP, 2020)*

### 2.3.2 NCS Practices/Scenarios

Despite representing a smaller sector of the Maine economy than forestry, 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 farmer yields and profits per acre. NCS practices can be adopted by farmers with operations of all sizes and production methods. 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 2. Additional details are provided below and in Appendix B.

*Table 2. 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 for enhanced soil organic carbon accumulation; reduce erosional soil losses, enhance water infiltration, reduce N losses ($N_2O$, $NO_3$) | potatoes, corn, other grains, vegetables |
| Intensive to reduced till | Permanently switch to reduced till farming that is targeted on 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 disturbance of the soil | corn, other grains, vegetables |
| Intensive to no till | Permanently switch to no-till farming for enhanced soil organic carbon accumulation through less disturbance | corn, other grains, vegetables |

| | | |
|---|---|---|
| | of the soil | |
| 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, reduced GHG losses and nutrient runoff | potatoes, corn, other grains, vegetables, hay, blueberries, apples |
| Manure amendment | Substitute fertilizer with manure and compost for reduced $CO_2$, $CH_4$, and $N_2O$ losses | potatoes, corn, other grains, vegetables, hay, blueberries, apples |
| Perennial set asides | Permanently convert crop and pasture to no-harvest set aside grassland. 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 | 1 digester per 2500 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 | 1 digester per 300 cows |
| Soild-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, 1 SLS per 1000 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 | 1 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 | 1 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 relative 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.[3] The NCS practices included cover crops, reduced-till, no-till, biochar amendments, amending soils with manure, manure management, and perennial set-asides (Table 3). GHG emissions factors and sequestration for the model baseline and NCS practices were based on 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.,

[3] Due to lack of data, we were unable to model the impact of climate change on crop yields.

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-level. Most of the results in the main report are presented at the aggregate state level, while more detailed results are presented 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 (*2017 Census of Agriculture*, 2019). Baseline crop production area values were: 50,211 acres of harvested potato, 38,660 acres of lowbush blueberry, 175,231 acres of hay and haylage, 32,571 acres of corn grown for grain and silage, 39,419 acres of other grains, 7,441 acres of apples and other perennial crops, and 12,028 acres of vegetables other than potato. In developing Table 3, several assumptions were made. All area currently in no-till production (21,676 acres) was assumed to be in silage or grain corn systems.[4] Area in reduced tillage (31,953 acres) was split between potato, other vegetables, and other grains.[5] Given uncertainty around the proportion of potato rotation crops reported as cover crops vs. small grains, we used the sum of harvested potatoes in the top three potato-producing counties (49,772 acres) as an estimate for cover crop adoption, assuming a 1:1 rotation.[6] The area of other vegetable land in cover crops was assumed to be the total (55,462 acres) minus the amount in potato systems. The total value of other grains was assumed to be equivalent to additional cover crop land, since small grains often function as cover crops. We assumed that all annual systems could be transitioned to rotations that are more diverse than what is currently implemented and therefore we assigned starting values of zero.[7] Current adoption of biochar amendments was assumed to be zero based on our understanding that this practice is uncommon at present.[8] 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) were assumed to have implemented this practice, with the remainder (45,629 acres) allocated to hay and haylage.[9]

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

[5] 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 (N. Lounsbury, unpublished data, February 26, 2020) we assumed a large fraction of vegetable land (50%; 6,104 acres) is employing some form of reduced tillage. The potato acreage employing a reduced tillage practice such as one-pass hilling was estimated by adding the area of potatoes harvested in the top three potato-producing counties assuming a 1:1 rotation (99,544 acres) and subtracting the total land in intensive production in these counties (81,030 acres) to arrive at 18,514 acres. The 13,439 reduced tillage acres remaining from the statewide total was assigned to other grains.

[6] Informed by data from potato farmer focus group (N. Lounsbury, unpublished data, January 23, 2020) indicating this rotation is common.

[7] The meaning of 'diverse rotations' varies by system and can overlap with cover crop adoption.

[8] N. Lounsbury, unpublished data, January 23, 2020; S. O'Brien, unpublished data, Fall 2019.

[9] 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.

*Table 3. Estimated Baseline Area in NCS Practices for Maine (acres)*

| Major Crop | Total Crop Area* | No-till | Reduced tillage | Cover crop | Diverse rotations | Biochar Amend | Amend w/ manure | Convert to perennial set-aside | Riparian Buffer |
|---|---|---|---|---|---|---|---|---|---|
| Potato | 50,211 | X | 18,514 | 49,772 | 0 | 0 | 0 | 0 | 0 |
| Lowbush blueberry | 38,660 | X | X | 0 | X | 0 | X | X | 0 |
| Hay & haylage | 175,231 | X | X | X | X | 0 | 45,629 | X | 0 |
| Silage & grain corn | 32,571 | 21,676 | 0 | 0 | 0 | 0 | 29,314 | 0 | 0 |
| Other grains | 39,419 | 0 | 13,439 | 39,419 | 0 | 0 | 0 | 0 | 0 |
| Apples & other perennials | 7,441 | X | X | X | X | 0 | X | X | 0 |
| Other vegetables | 12,028 | 0 | 6,014 | 5,690 | 0 | 0 | X | 0 | 0 |
| Total Study Area | 355,561 | 21,676 | 37,967 | 94,881 | 0 | 0 | 74,943 | 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

### 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 4 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 4. 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 | 240 cwt | $10 | $2,510 | $1,382 | $1,129 | 2.11 |
| Blueberries | 4,445 pounds | $0.47 | $2,102 | $1,504 | $598 | 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 | $22,117 | $17,276 | $4,841 | 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 (*2017 Census of Agriculture*, 2019). Soil amendments with biochar and manure are NCS practices that can be implemented in orchards. We 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 $2230/bfa in net revenue per year. Additional information about the apple system is available in Appendix B.

***Blueberries***

Approximately 60,000-65,000 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 66 and 70 million pounds of blueberries are produced annually in Maine (Drummond et al., 2009; Rose et al., 2013). 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 $1,504/ac in total costs. As a result, the system produced an average of $598/ac in net revenue per year. 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 < 50 cows. The current 218 commercial-scale dairy farms house an estimated 28,000 cows.[10] 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 2-3 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 which 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 lack of contiguous fields raises costs of manure transport.[11] 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[12]. 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. Several NCS practices can be implemented for grains, including no-till, reduced tillage, cover crops, and soil

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

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

[12] N.B., the negative net revenue for dairy over the 5 year period of our data maybe 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.

amendments. We estimated that, on average, the net revenue for barley, corn silage, and wheat were -$139/ac, -$205/ac, and $532/ac, respectively. When coupled with a dairy farm, the negative net revenue per acre for barley and corn silage can be offset as feed for livestock. 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, 174,000 acres of farmland in Maine are used for forage, including hay (*2017 Census of Agriculture*, 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, helping to manage weeds and maintain hayfield productivity (Kersbergen, 2004). More intensive management of hayfields including occasional tillage and re-seeding of desired species, as well as 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.

***Potato***

Potatoes are a high-value crop, but also expensive to grow.[13] Approximately 50,000 acres of potatoes in Maine were grown in 2017 (*2017 Census of Agriculture*, 2019) for three key markets: processing (~30,000 acres), seed (~11,000 acres), and tablestock (~9,000 acres).[14] Most growers are using a 1:1 rotation with one year of potatoes and one year of a much less valuable cash crop like a grain, or an unharvested cover crop. Some growers are using a 2:1 rotation with a longer "off" period from potatoes.[15] 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. Despite the adoption of one-pass hilling by some growers, potato cropping systems remain by necessity tillage-intensive. We estimated that, on average, a typical potato system made $2,510/ac in revenue and had $1,035/ac in variable costs and $347/ac in annualized fixed costs. As a result, the system produced $1,129/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 growing fresh market vegetables (not including potato farms) harvested for sale in 2017. Some of the prevalent crops are snap beans, potatoes, peppers, squash, sweet corn, and tomatoes (*2017 Census of Agriculture*, 2019). Diversified vegetable systems usually rely on regular tillage, both for weed control and preparation of a seedbed for

[13] J. Jemison, personal communication, February 2018
[14] J. Jemison, personal communication, February 2018.
[15] N. Lounsbury, unpublished data, January 23, 2020.

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. Cover cropping is utilized by many diversified vegetable farmers at present, but their use of the practice is sometimes constrained by limited acreage and the opportunity cost of taking land out of production.[16] Further 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 $22,117/ac in revenue and had $11,724/ac in variable costs and $5,552/ac in annualized fixed costs. As a result, the system produced $10,394/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 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 (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 sensitivity of GHG mitigation factors from this analysis due to the wide variation in max and min estimates. Furthermore, we did not analyze the effect of climate change on crop yields and mitigation potential due to lack of data.

# 3. Results

## 3.1 Forestry

### 3.1.1 Model Baseline

Circa 2010, LANDIS-II estimates based on initial forest conditions indicated there was approximately 1.33 Tg of aboveground carbon distributed broadly across our study area (Figure 7). At the cell-level, aboveground carbon ranged from 116-7,976 g $m^{-2}$, with an average of 4,250 g $m^{-2}$, reflecting complex variation in tree species relative abundance and forest age across northern Maine.

[16] R. Clements, unpublished data, 2019.

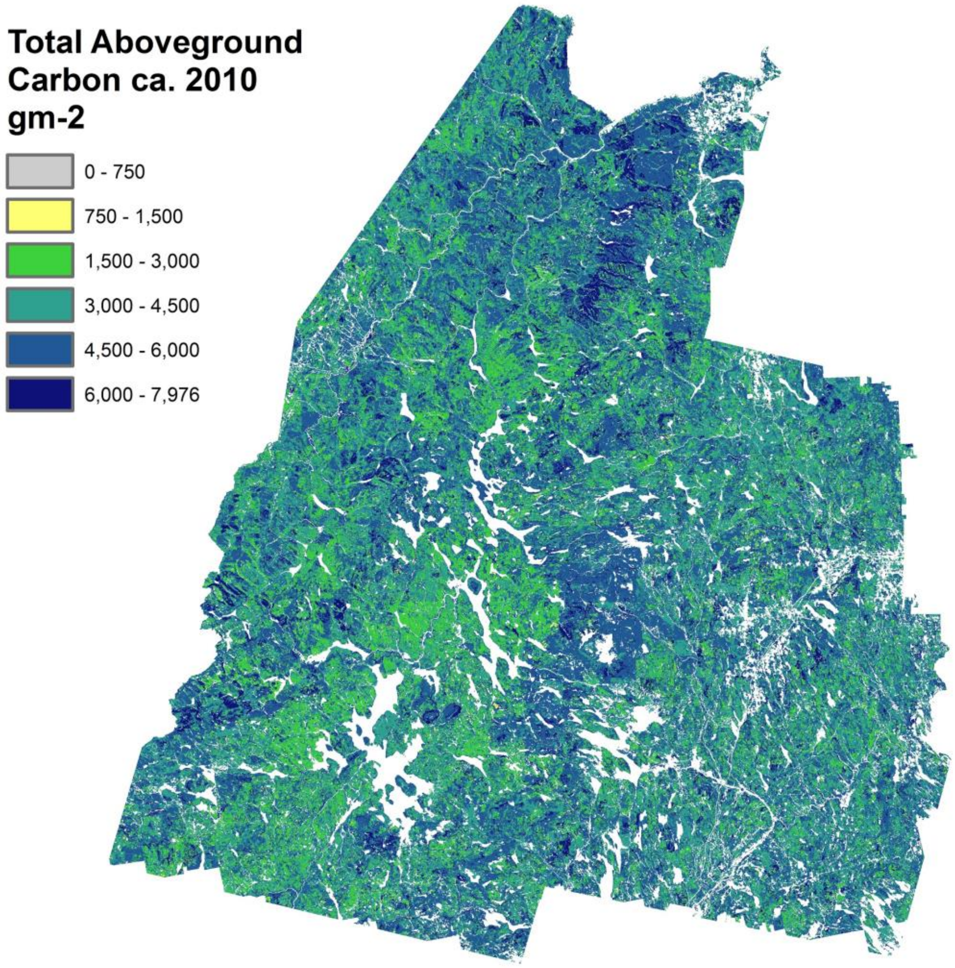


*Figure 7. Spatial distribution of total aboveground carbon ca. 2010, also representing the starting conditions for forest landscape simulations 2010-2070.*

Under the baseline (i.e., BAU min50 under RCP 2.6) scenario total aboveground carbon declined 7%, from approximately 1.33 Tg to 1.24 Tg, between 2010 and 2070 (Figure 8). On average 0.27 Tg of aboveground carbon was projected to be harvested every 10 years. The average total harvest footprint every 10 years was projected to be 1,486,963 acres, which translated into an annual harvest rate of approximately 1.7% for the study area.

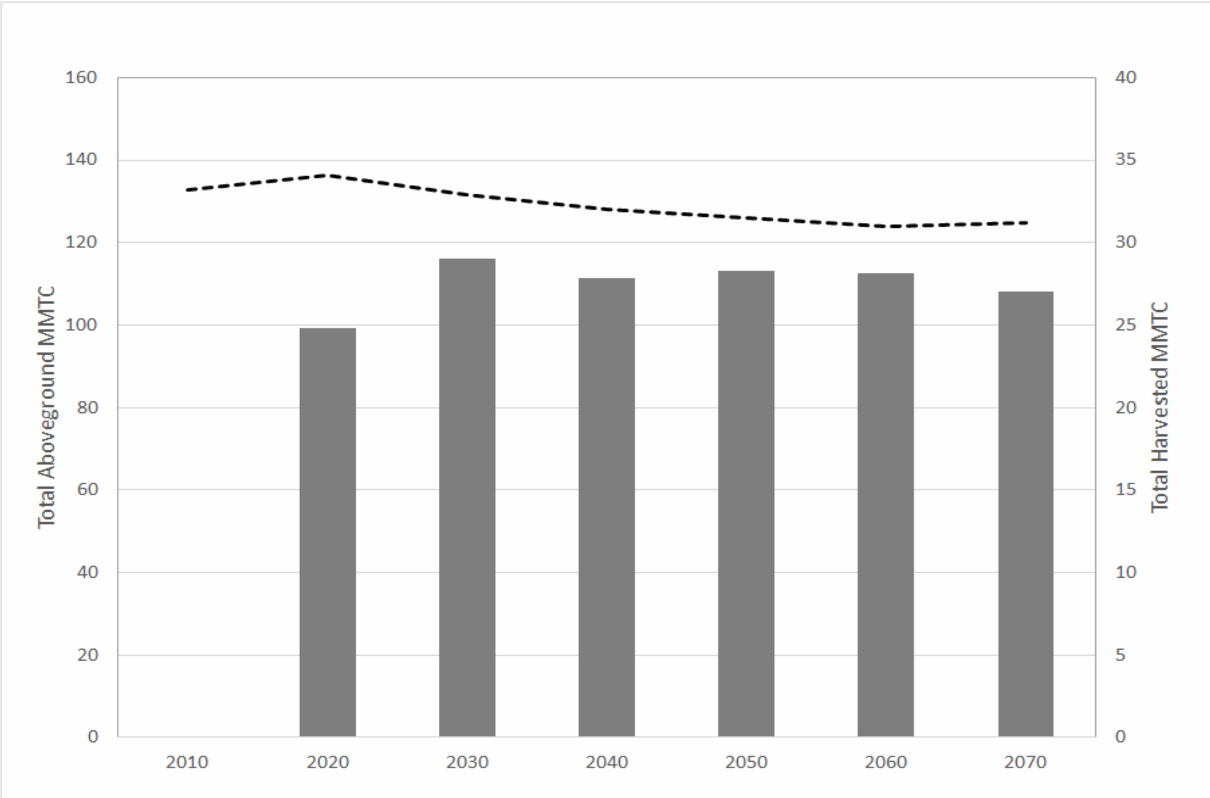


*Figure 8. Total, live aboveground million metric tons of carbon (MMTC) (standing; dashed line) and total harvested MMTC (gray bars) every 10 years (e.g., 2010-2020, 2020-2030, etc.) under the baseline or Business-as-usual (BAU) scenario, 2010-2070.*

Harvest levels in the 9.1 m 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 the relevant 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/yr in stumpage revenue. These estimates were the values for which all the other Landis-based scenarios were compared against in this study.

### 3.1.2 Forest NCS practice results

#### *3.1.2.1 Forest management in Landis*

Total aboveground carbon followed a wide variety of trends, including increasing and declining, under RCP 2.6 and the different management scenarios (Figure 9). In general, total aboveground carbon was lower than the initial amount under the extended rotation scenarios, with the exception of the Min 100 years, which was the only scenario that projected a reversal in direction (rapidly increasing until 2040 and then rapidly declining). Increased clearcutting also resulted in a declining trend unless paired with planting. A set-aside resulted in a relatively stable aboveground carbon pool at 10%, or slightly increasing at 20%. Circa 2070, all scenarios were higher than BAU min50, ranging from +1% (35% clearcut) to +40% (50% clearcut, plant or 35% clearcut, plant, 20% set-aside).

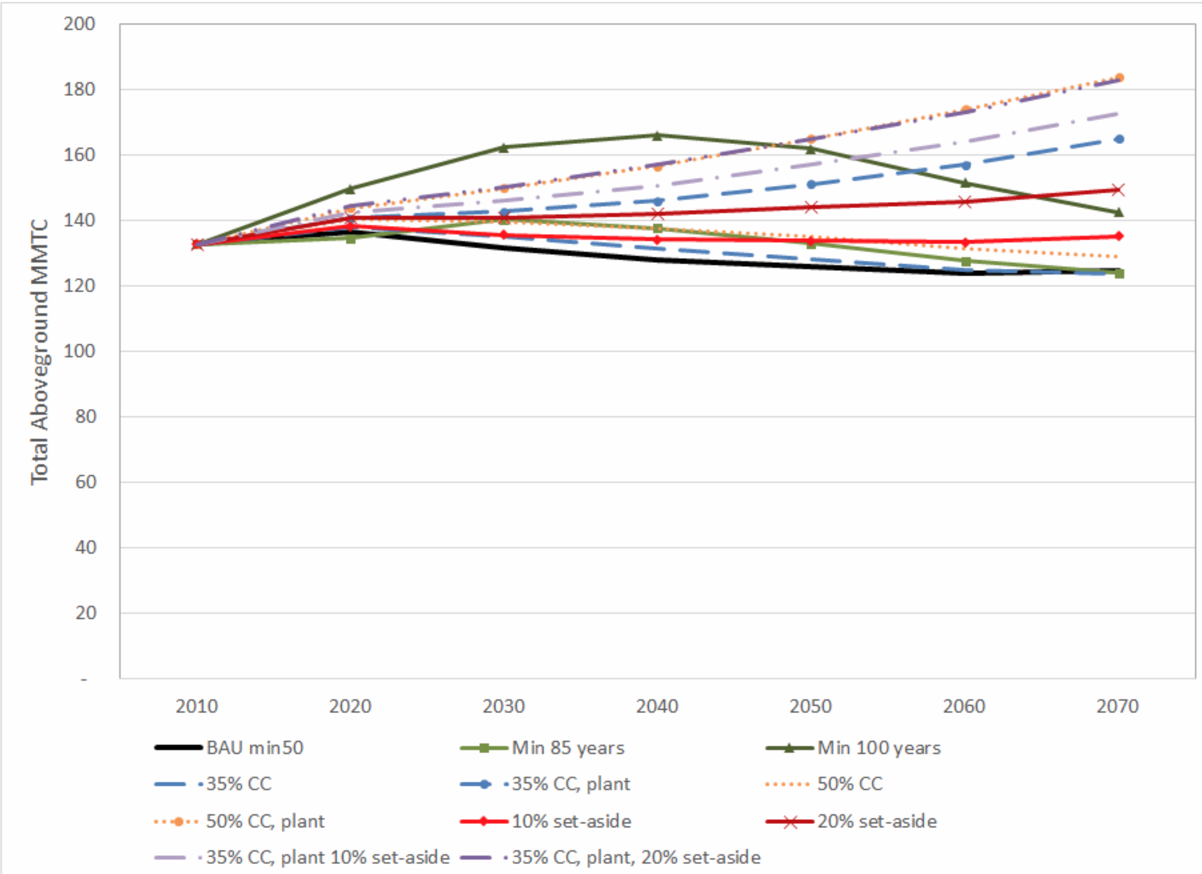


*Figure 9. Comparison of total aboveground carbon stock (MMTC) under RCP 2.6 and the different forest management scenarios 2010-2070. See Table 1 for scenario descriptions.*

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 doing so relative to the BAU (typically in the form of lost revenues or increased planting and management costs). Figure 10 indicates that extending the minimum stand age before harvest out to 100 years increased forest carbon over the first 20 years as many stands that were harvested under BAU were left to mature. However, those increases in carbon diminish 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 20% of total forest area established as no-harvest set asides resulted in a noticeable reduction in timber harvests (13-17% below BAU) over the next 50 years (Figure 11). 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 supply across the landscape suggests that there could be minimal 'leakage' of forest carbon loss to other parts of the globe as a result of implementing forest NCS in Maine.

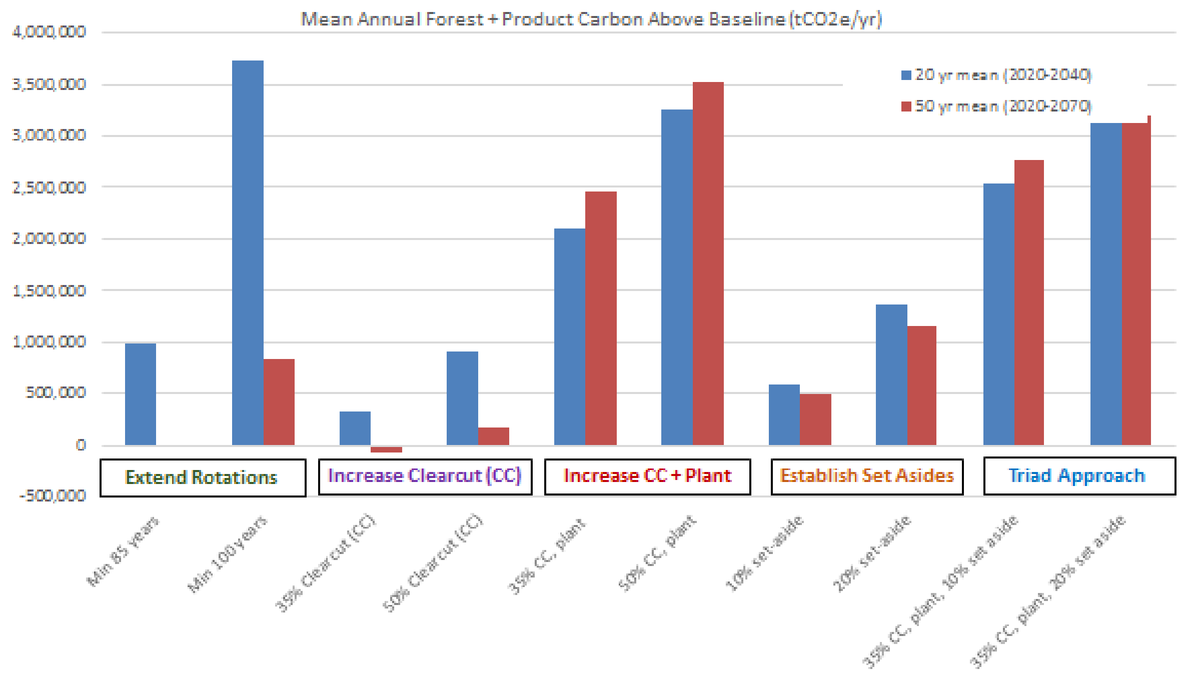


*Figure 10. Mean annual forest and harvested wood product carbon change from BAU.*

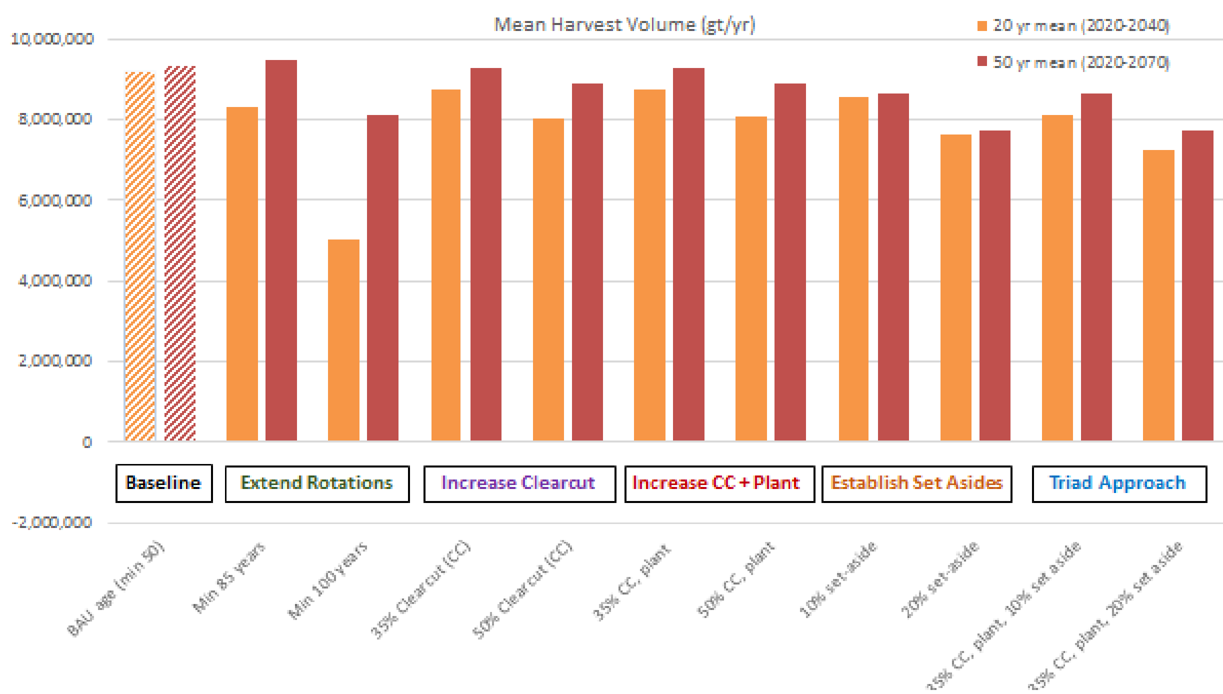


*Figure 11. Mean annual timber harvest volume.*

The modeled scenarios indicate changes in total timber harvests (and revenue) coupled with increased costs associated with the planting scenarios will result in overall total costs for implementing these NCS relative to the BAU (Figure 12). The 100min 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. Of course, those higher costs resulted in greater amounts of carbon being sequestered on the stump and harvested wood products, thereby reducing the break-even carbon price that a landowner may be willing to receive to implement a specific practice (Figure 13). 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/tCO2e, which is relatively inexpensive compared to most non-NCS opportunities.

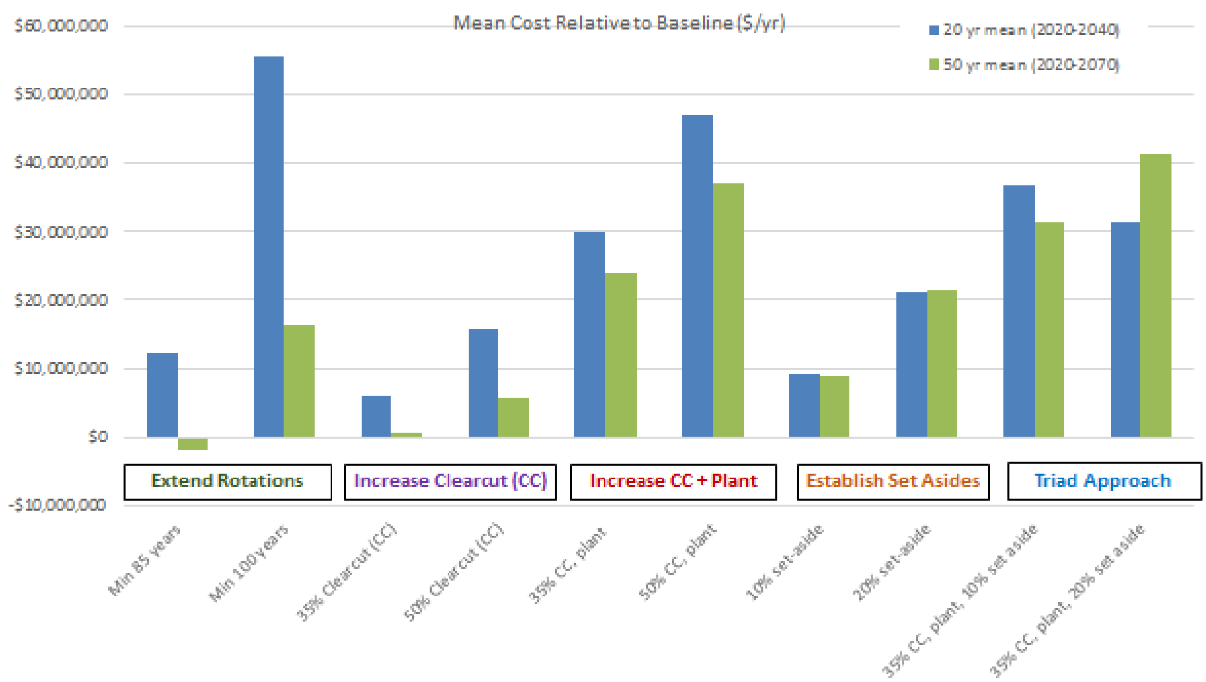


*Figure 12. Mean total annual mitigation cost relative to BAU*

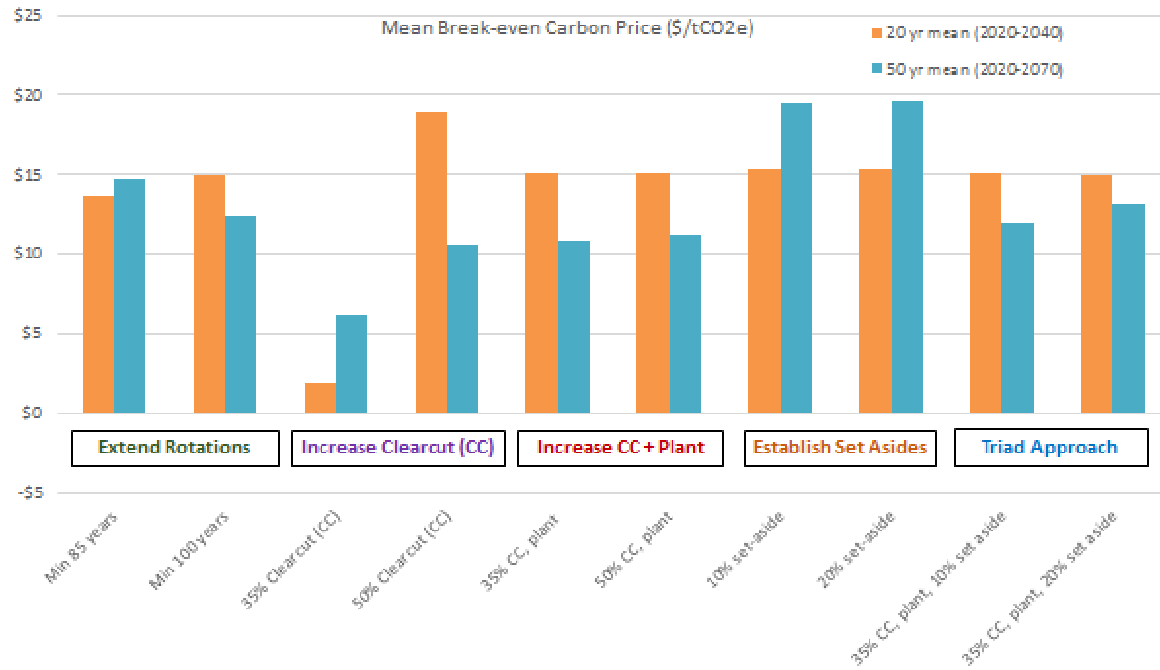


*Figure 13. Mean break even carbon price*

While our results are largely presented at the nine million acre study level, the Landis-modeling framework also allows one to assess impacts at a species and habitat level. Some of these aspects are summarized in Table 5. As presented above, total timber harvest was lower under all forest management scenarios relative to the baseline (BAU min50) 2010-2060, ranging from less than 0.5% lower under the 35% clearcut with or without planting to 13% lower under extended rotation to a minimum age of 100 years. However, the forest management scenarios varied widely in the impact on the ecosystem services we considered. Spruce-fir carbon increased under all scenarios, except 35% clearcut without planting. As with total aboveground carbon, planting after clearcutting increased spruce-fir carbon. Late successional (LS) forest for both spruce-fir (SF) and northern hardwood (NH) forest declined under Min 100 but increased with the addition of a 10% forest set-aside. LS results under the 35% clearcut scenarios varied, but lynx foraging habitat increased under all three. Lynx habitat decreased with extended rotation (Min 100) or 10% forest set-aside.

*Table 5. Comparison of select forest NCS model outputs ca. 2060 under a subset of forest management strategies and RCP 2.6, including mean break even carbon price, and relative difference (compared to BAU min50) in total harvest, spruce-fir total aboveground carbon, late successional spruce-fir (SF) or northern hardwood (NH) forest, and lynx foraging habitat.*

| Scenario | Break even carbon price ($/t$CO_2$e) | Total harvest 2010-2060 | Spruce-Fir C | LS forest Change | | Lynx habitat Change |
|---|---|---|---|---|---|---|
| | | | | SF | NH | |
| Min 100 years | $12 | -13% | 33% | -8% | -13% | -25% |
| 10% set-aside | $20 | -7% | 10% | 4% | 4% | -3% |
| 35% CC | $6 | -0.4% | -4% | -12% | 4% | 33% |
| 35% CC + plant | $14 | -0.3% | 117% | 9% | -7% | 487% |
| 35% CC + plant + 10% set-aside | $12 | -8% | 118% | -4% | 0% | 427% |

#### *3.1.2.2 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 low to high intensity development was estimated to be feasible on about 360,000 acres of land across the state (Cook-Patten et al., 2020). The average afforested stand was estimated to sequester 2.1 t$CO_2$e/ac/yr, thereby yielding a total of 760,000 t$CO_2$e/yr in additional carbon sequestration. Implementing this NCS across Maine was estimated to cost about $22.8 million/yr, or $30/t$CO_2$e.

Incentivizing forest landowners to avoid converting their land to other uses has a wide range of costs depending on where the forest under threat is located in the state and what it is expected to be converted to. Following the historical trend that about 2,000 acres per year of forest is converted to agriculture in the state, we estimated that this could be avoided at a cost of about $21/t$CO_2$e, thereby sequestering an average of 200,000 t$CO_2$e/yr over the next 50 years. The cost of avoided conversion to developed land was much higher due to the expected land value associated with that land use. As a result, it could cost about $700/t$CO_2$e to keep the 6,500 acres of forest threatened by development every year as forests in perpetuity[17]. If there was a willingness to pay this amount, then about 685,000 t$CO_2$e/yr could be sequestered on average over the next 50 years by these 'protected' areas.

#### *3.1.2.3 Summary of core modeled results*

The 50-year average estimates of key results from all the forest NCS practices evaluated are summarized in Figure 14. The figure shows that many of the top mitigation options are expected to come from

[17] N.B., because an additional 8,500 acres of 'new' land is threatened by conversion each year, the total amount of land that needs to be protected increases over time. As a result, over 420,000 acres of forest area could potentially be spared from conversion under this approach by 2070.

increasing clearcuts and planting and/or permanent set-asides. In addition, afforesting marginal pasture and cropland could also provide additional mitigation in addition to the improved forest management. We find that the average break-even carbon prices for most forest NCS practices are in the range of \$10-20/t$CO_2$e. Additionally, if landowners could collectively change forest management across the 9.1 million acres in northern Maine from BAU to 50% clearcut followed by planting in addition to afforesting marginal land *and* reducing conversion of forests to cropland across the state, we estimate that it could yield about 4.5 Mt$CO_2$e/yr in additional carbon sequestration at a cost of \$64 million/yr or \$14/t$CO_2$e.

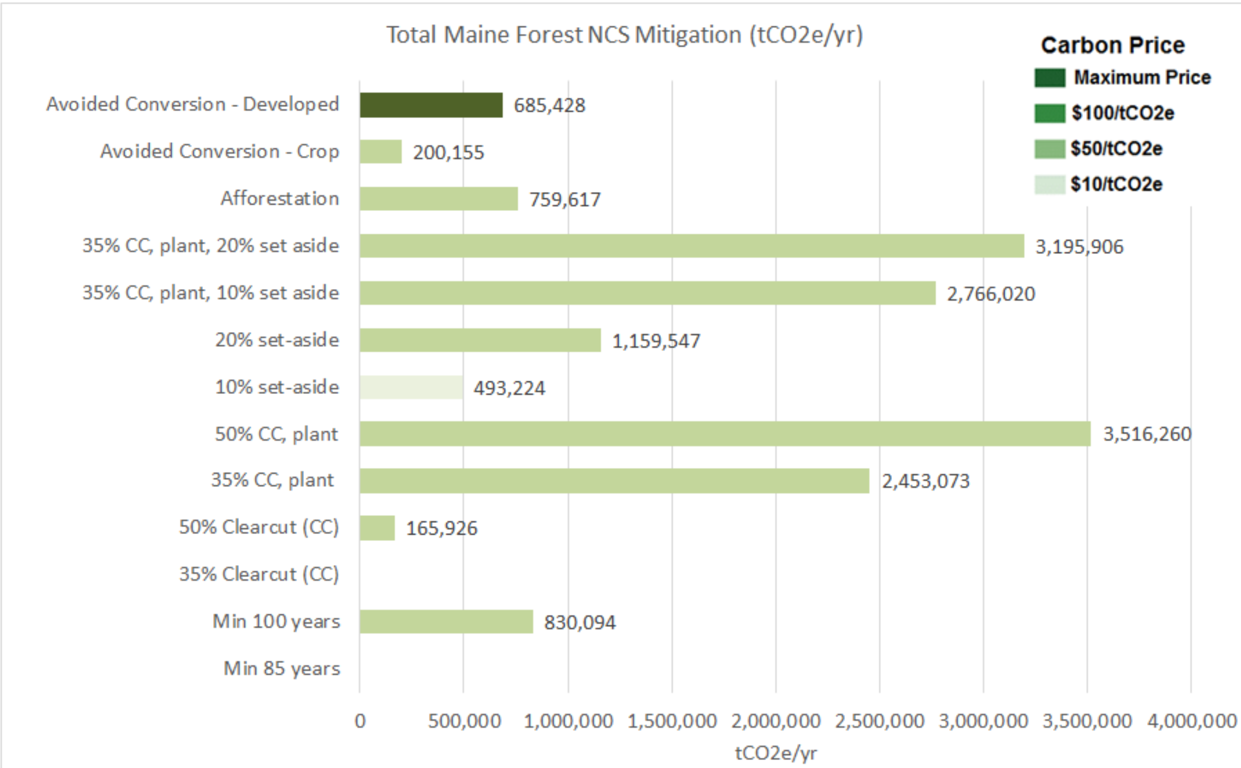


*Figure 14. Total Maine forest NCS mitigation potential (tCO2e/yr), 2020-2070 annual average, RCP 2.6. (Note: the avoided conversion and afforestation scenarios cover the entire state, while the other scenarios only include 9.1 million acres of managed forest in Northern Maine.)*

### 3.1.3 Sensitivity Analysis

#### *3.1.3.1 Climate change impacts sensitivity*

Total forest carbon was generally higher under the high emission scenario (RCP 8.5) across all management scenarios, until 2050 (Figure 15). Beginning with the 2050-2060 interval (blue bar, Figure 15), 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. Across all scenarios, this difference increased 2060-2070 (dark blue bar, Figure 15).

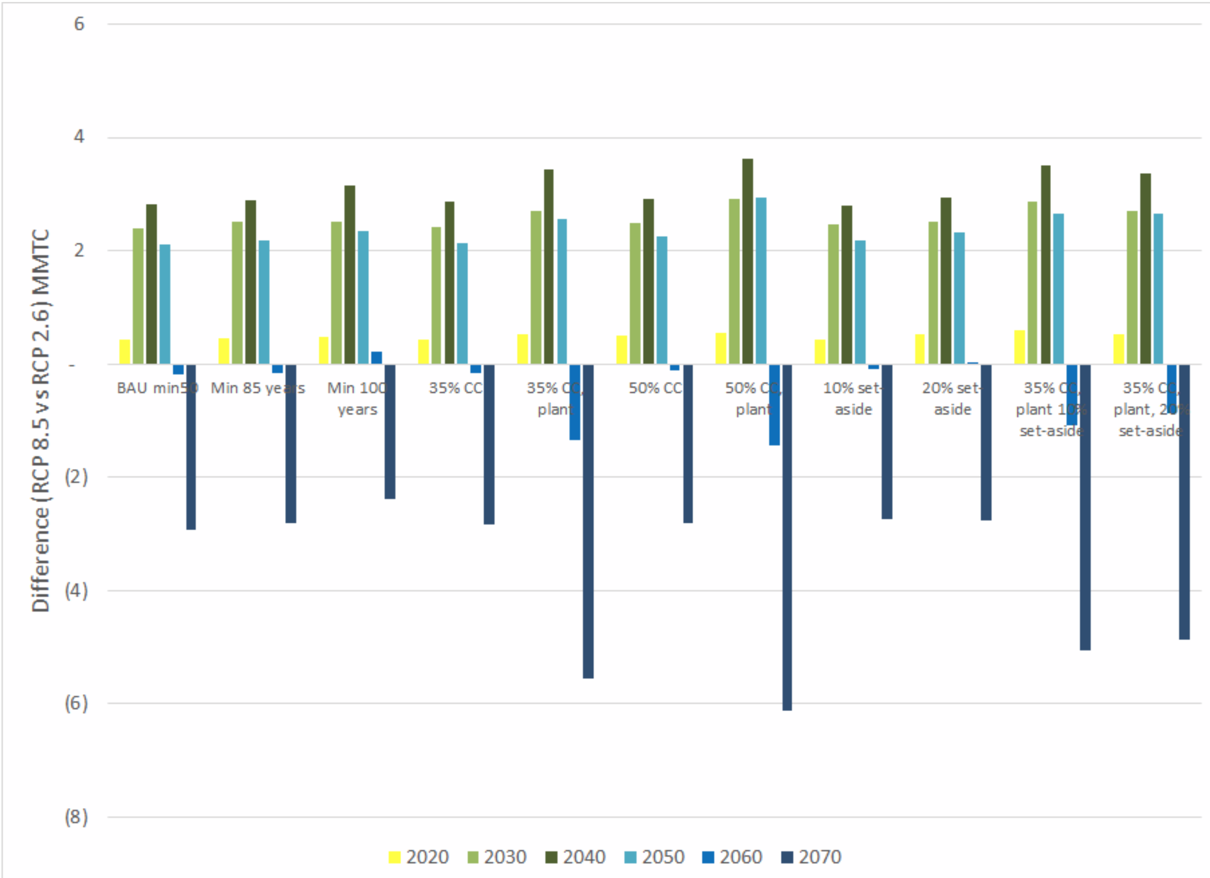


*Figure 15. Difference in MMTC, across scenarios, for aboveground carbon per interval between RCP 8.5 and RCP 2.6. A positive difference indicates that total forest carbon stock was higher in a given interval (e.g., 2010-2020) under RCP 8.5.*

Table 6 summarizes the key differences between RCP 2.6 and RCP 8.5 estimates based on a 50-year annual mean over 2020-2050. 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. Mean harvest volume only differed by 1% between the two RCPs, which was by design in our modeling exercise.

*Table 6. Key RCP 8.5 model estimates and difference 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 | -12,935 | -29% | 9,573,938 | 1% | -$1.8 | -4% | $15 | -2% |
| Min 100 years | 856,688 | 3% | 8,189,758 | 1% | $16.6 | 2% | $12 | 0% |
| 35% Clearcut (CC) | -66,115 | -5% | 9,388,191 | 1% | $0.6 | 18% | $6 | -5% |
| 50% Clearcut (CC) | 170,936 | 3% | 8,986,382 | 1% | $6.0 | 1% | $10 | -6% |
| 35% CC, plant | 2,290,789 | -7% | 9,397,854 | 1% | $24.2 | 0% | $11 | 3% |
| 50% CC, plant | 3,317,819 | -6% | 9,006,471 | 1% | $37.3 | 0% | $11 | 3% |
| 10% set-aside | 501,816 | 2% | 8,746,120 | 1% | $9.2 | 2% | $19 | -1% |
| 20% set-aside | 1,315,509 | 13% | 7,728,575 | 0% | $22.7 | 7% | $19 | -5% |
| 35% CC, plant, 10% set aside | 2,631,673 | -5% | 8,718,366 | 1% | $31.6 | 1% | $12 | 4% |
| 35% CC, plant, 20% set aside | 3,073,542 | -4% | 7,795,875 | 1% | $41.6 | 1% | $14 | 4% |
| Afforestation | 735,443 | 0% | 9,264,829 | 1% | $22.1 | 0% | $30 | 0% |
| Avoided Conversion - Crop | 100,086 | 0% | 9,264,829 | 1% | $2.1 | 0% | $21 | 0% |
| Avoided Conversion - Developed | 341,358 | 0% | 9,264,829 | 1% | $239.9 | 0% | $703 | 0% |

#### *3.1.3.2 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 7). On the contrary, 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 undertaking 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 7. Change in forest NCS mitigation costs for stumpage price and planting sensitivity analysis*

| Scenario | Total Cost (Mil $/yr) | | | | Break-even carbon price ($/t$CO_2$e) | | | |
|---|---|---|---|---|---|---|---|---|
| | *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 - Crop | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Avoided Conversion - Dev | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

## 3.2 Agriculture

### 3.2.1 Model Baseline

The agricultural sector model baseline estimates are listed in Table 8. 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 $246 million/yr in net revenue (i.e., profit) once you take into account capital and operating expenses. These baseline farm enterprises emitted about 320,000 t$CO_2$e/yr of GHGs, but also sequestered about 42,000 t$CO_2$e/yr through activities such as no till and cover cropping.

*Table 8. 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 |

The baseline Maine agricultural sector GHGs and carbon sequestration are shown in Figure 16. When adding the 67,000 $tCO_2e$/yr of non-dairy livestock emissions to our estimates in Table 8, we estimated that gross GHGs are equal to about 387,127 $tCO_2e$/yr, while carbon sequestration from current NCS practices reduced the sector footprint by 42,345. 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.

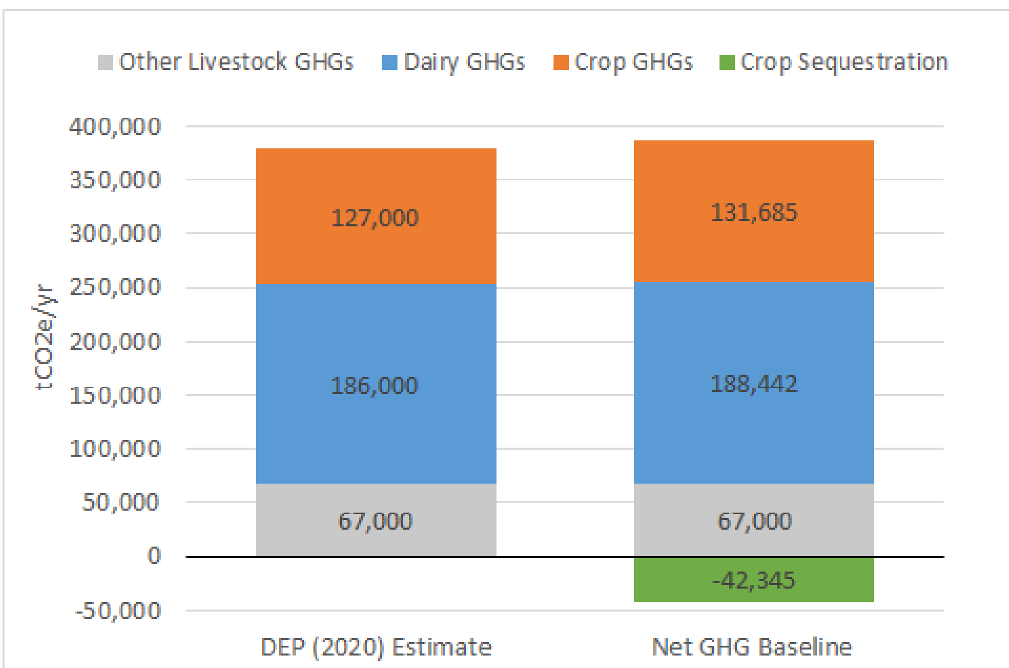


*Figure 16. Maine DEP (2020) and modeled baseline agricultural sector GHG emissions.*

### 3.2.2 Agriculture NCS practice results

Applying our core (i.e., 'medium') agricultural sector model assumptions about mitigation potential, yield change, and practice costs, we estimate that there is wide variation in potential from implementing agricultural NCS in Maine (Figure 17). 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 of these could be implemented at relatively low cost as well, in the range of \$25-34/$tCO_2e$ (Table 9). The large mitigation potential is primarily a factor of two things. First, both of these 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 a large 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, while they are likely to produce additional co-benefits such as improved soil health and water quality.

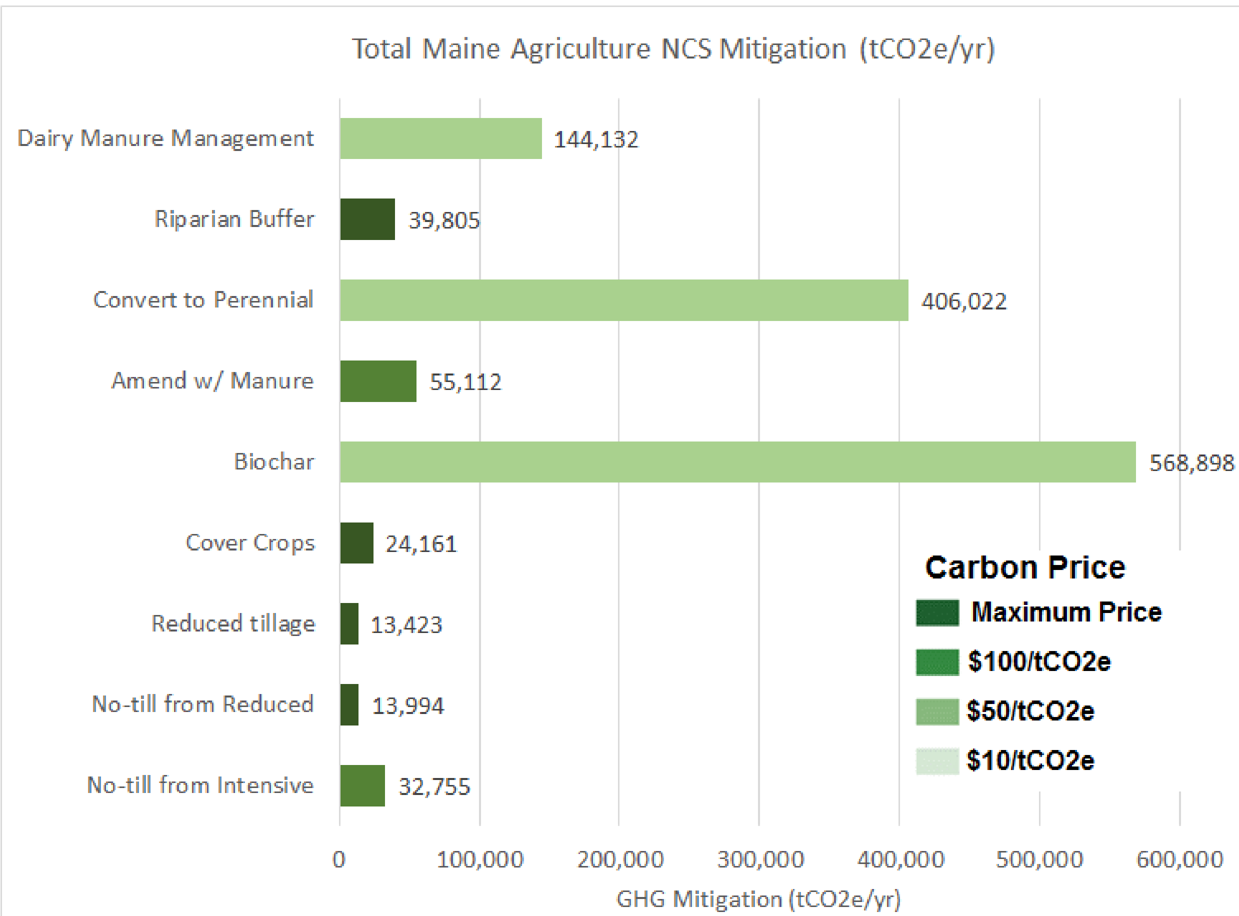


*Figure 17. Total Maine agriculture NCS mitigation potential (tCO2e/yr).*

The Maine agricultural NCS model estimates by specific crop are summarized in Table 9. 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 highlights that mitigation has the potential to come from a wide range of crops.

*Table 9. Maine agricultural NCS practice estimates by crop.*

| NCS Practice | Hay | Potato | Blueberry | Wheat | Corn | Barley | Veg. | Apples | Dairy | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| *Annual Mitigation ($tCO_2e/yr$)* | | | | | | | | | | |
| No-till from Intensive | 0 | 0 | 0 | 8,968 | 14,820 | 8,968 | 0 | 0 | 0 | 32,755 |
| No-till from Reduced | 0 | 0 | 0 | 6,997 | 0 | 6,997 | 0 | 0 | 0 | 13,994 |
| Reduced tillage | 0 | 5,021 | 0 | 1,971 | 3,257 | 1,971 | 1,203 | 0 | 0 | 13,423 |
| 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 | 280,370 | 80,338 | 61,856 | 31,535 | 52,114 | 31,535 | 19,245 | 11,906 | 0 | 568,898 |
| Amend w/ Manure | 27,161 | 7,783 | 5,992 | 3,055 | 5,049 | 3,055 | 1,864 | 1,153 | 0 | 55,112 |
| Convert to Perennial | 225,224 | 42,545 | 0 | 22,961 | 40,700 | 14,552 | 17,273 | 0 | 0 | 363,255 |
| Dairy Manure Management | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 119,139 | 119,139 |
| Riparian Buffer | 28,789 | 5,302 | 0 | 476 | 1,629 | 384 | 836 | 0 | 0 | 37,418 |
| *Annual Mitigation Cost (Mil $/yr)* | | | | | | | | | | |
| No-till from Intensive | $0.0 | $0.0 | $0.0 | $1.7 | $0.6 | $0.7 | $0.0 | $0.0 | $0.0 | $3.0 |
| 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 | $1.1 | $0.0 | -$0.1 | $0.6 | $0.5 | $0.3 | $0.0 | $0.0 | $2.3 |
| 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 | $7.1 | $2.0 | $1.6 | $0.8 | $1.3 | $0.8 | $0.5 | $0.3 | $0.0 | $14.5 |
| Amend w/ Manure | $2.4 | $0.7 | $0.5 | $0.3 | $0.4 | $0.3 | $0.2 | $0.1 | $0.0 | $4.9 |
| Convert to Perennial | $7.7 | $1.8 | $0.0 | $0.7 | $1.1 | $0.7 | $0.4 | $0.0 | $0.0 | $12.4 |
| Dairy Manure Management | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $0.0 | $2.6 | $2.6 |
| 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 | $90 |
| 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 | $174 |
| 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 | $41 | $0 | $30 | $28 | $48 | $24 | $0 | $0 | $34 |
| Dairy Manure Management | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $22 | $22 |
| Riparian Buffer | $124 | $124 | $0 | $106 | $103 | $132 | $95 | $0 | $0 | $122 |

All of these practices are presented as a single-focused implementation on a given parcel of land. In reality, some of these practices can be 'bundled' and applied simultaneously. In addition, 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 waste. If these options were simultaneously implemented across all eligible farms, then Maine could expect to mitigate up to 786,000 $tCO_2e$/yr in agricultural GHG emissions or about double the sector's current annual emissions. This combined approach is estimated to cost $26.3 million/yr or about $34/$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 10). Breaking out dairy by specific NCS practices , which were primarily different sized and types of anaerobic digesters (AD), reveals that the larger 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 waste 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 is often made up of small herds (*2017 Census of Agriculture*, 2019). As a result, widespread implementation will likely require extensive cooperation, capital investment, and potentially long waste hauling distances to achieve the scale of mitigation that we have estimated.

*Table 10. 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 |

The model estimates were dependent on a wide range of assumptions about how NCS practices affect yield, cost, and mitigation potential.[18] 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 18, Figure 19). 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 $17.4 mil/yr ($22/$tCO_2e$) and a High cost of $47.1 mil/yr ($60/$tCO_2e$). While this range is found to be higher than most of the forest NCS practices, it is still well

[18] 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.

within the range of other NCS and land-based mitigation studies (Fargione et al., 2018; Griscom et al., 2017; Roe et al., 2019) as well as the cost of implementing non-NCS options like renewable energy (Riahi et al., 2017).

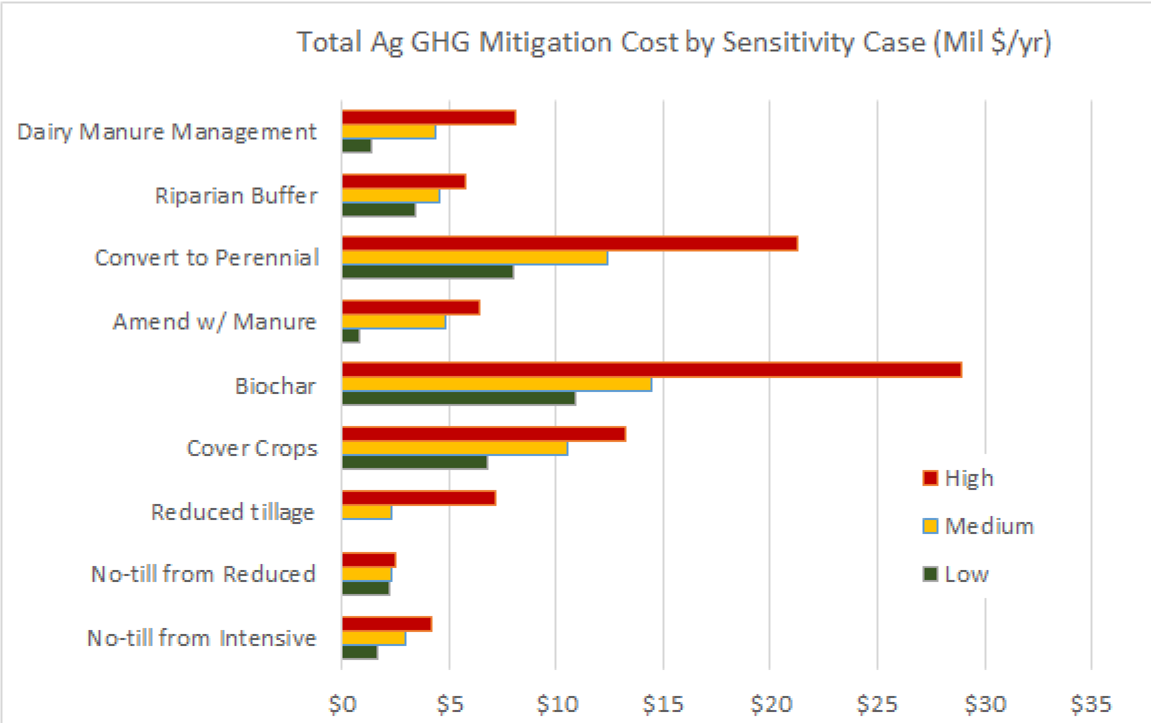


*Figure 18. Total annual Maine agriculture NCS practice cost (mil $/yr) by sensitivity case.*

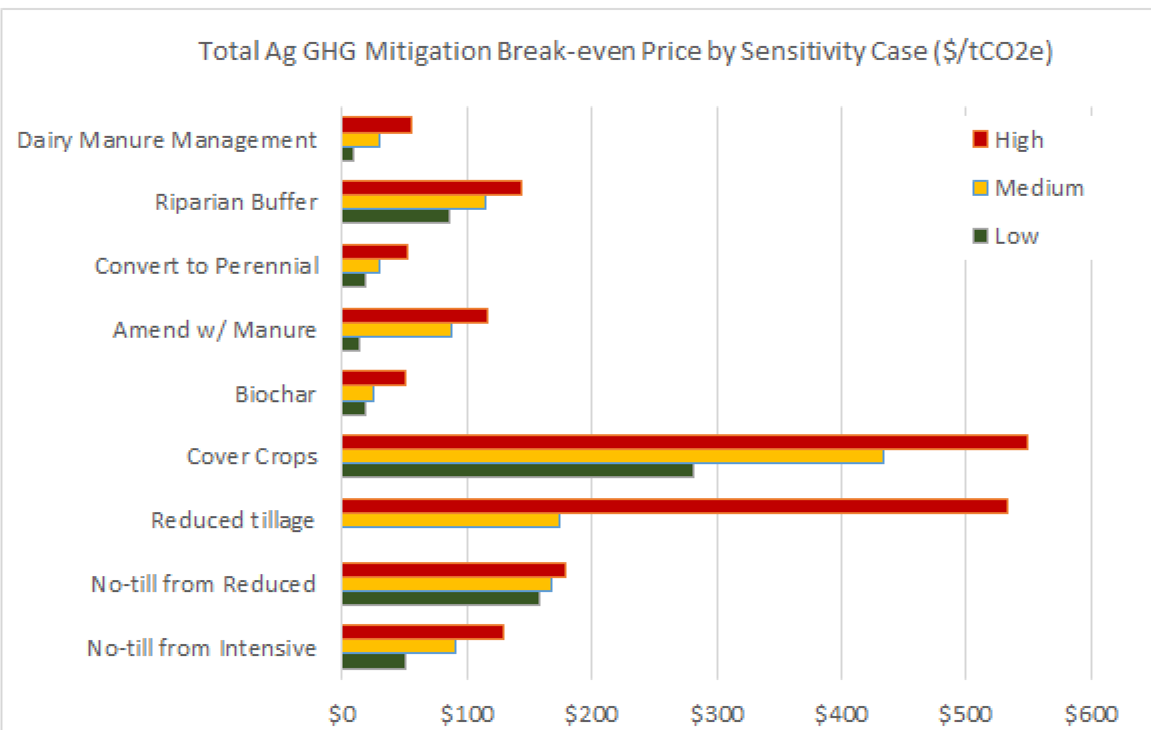

*Figure 19. Total annual Maine agriculture NCS practice break-even carbon price ($/tCO2e) by sensitivity case.*

# 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 are listed in Table *11*. Based on this assessment, we found that the following five practices for each of the forestry and agriculture sectors provided the most mitigation potential in Maine at relatively low cost.

Forestry:

1. 50% clearcut area + planting
2. 35% clearcut + 20% set aside
3. 35% clearcut + 10% set aside
4. 35% clearcut + planting
5. Afforest marginal crop and pasture

Agriculture:

1. Amend soil with biochar
2. Convert to perennial grasses
3. Dairy manure management
4. Amend soil with manure
5. Plant riparian buffers

The results in Table 11 present the impacts if specific practices were implemented on their own. However, in some instances, a subset of NCS practices can be implemented simultaneously, either on the same farm/stand or in separate areas, which will be explored in more detail in a future analysis. On the forestry side, 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 4.5 $MtCO_2e$/yr in additional carbon sequestration at a cost of $64 million/yr or $14/$tCO_2e$. In terms of agriculture, 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 waste, thereby mitigating up to 786,000 $tCO_2e$/yr in GHG emissions or about double the sector's current annual emissions. This combined approach for the agricultural sector is estimated to cost $26.3 million/yr or $34/$tCO_2e$.

With respect to forestry, our analysis found that annual harvests were reduced by 5% or less compared to the BAU, thereby ensuring a steady timber supply even with an increase in forest carbon. 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 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 11. Summary of key findings for Maine NCS mitigation potential*

| Land-use Sector | NCS Practice | GHG Mitigation ($tCO_2e/yr$) | Mitigation Cost ($/yr) | Break-even Carbon Price ($\$/tCO_2e$) | Total Applicable Area (acres or cows) |
|---|---|---|---|---|---|
| Forestry | BAU age (min 50) | 0 | $0.0 | $0 | 9,100,000 |
| | Min 85 years | -18,276 | -$1.9 | $15 | 9,100,000 |
| | Min 100 years | 830,094 | $16.2 | $12 | 9,100,000 |
| | 35% Clearcut (CC) | -69,900 | $0.5 | $6 | 9,100,000 |
| | 50% Clearcut (CC) | 165,926 | $5.9 | $11 | 9,100,000 |
| | 35% CC, plant | 2,453,073 | $24.1 | $11 | 9,100,000 |
| | 50% CC, plant | 3,516,260 | $37.1 | $11 | 9,100,000 |
| | 10% set-aside | 493,224 | $9.0 | $20 | 9,100,000 |
| | 20% set-aside | 1,159,547 | $21.3 | $20 | 9,100,000 |
| | 35% CC, plant, 10% set aside | 2,766,020 | $31.4 | $12 | 9,100,000 |
| | 35% CC, plant, 20% set aside | 3,195,906 | $41.3 | $13 | 9,100,000 |
| | Afforestation | 759,617 | $22.8 | $30 | 360,000 |
| | Avoided Conversion - Crop | 200,155 | $4.1 | $21 | 95,300 |
| | Avoided Conversion - Developed | 685,428 | $481.8 | $703 | 327,800 |
| Agriculture | No-till from Intensive | 32,755 | $3.0 | $90 | 71,990 |
| | No-till from Reduced | 13,994 | $2.4 | $168 | 39,419 |
| | Reduced tillage | 13,423 | $2.3 | $174 | 134,229 |
| | Cover Crops | 24,161 | $10.5 | $434 | 134,229 |
| | Biochar | 568,898 | $14.5 | $25 | 355,561 |
| | Amend w/ Manure | 55,112 | $4.9 | $88 | 355,561 |
| | Convert to Perennial | 406,022 | $12.4 | $30 | 241,346 |
| | Riparian Buffer | 39,805 | $4.6 | $115 | 21,309 |
| | 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 | $15 | 30,443 |
| | Small Complete Mix AD | 150,997 | $5.4 | $36 | 30,443 |
| | Plug Flow AD | 76,305 | $9.4 | $123 | 30,443 |

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 proven at the commercial level, 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. Dairy management relies on the investment in digesters, which require financial capital. Despite these potential 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 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.

Our results show limited carbon sequestration of the agricultural NCS practices in Maine compared to forestry. Our model also only assessed their impact on yield and net GHG emissions and no other 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. Further research could incorporate quantification of the potential co-benefits of NCS on aspects such as water quality and quantity and soil health. The analysis could also be extended to investigate interactions between the forestry and agricultural sectors.

Our analysis also assumed that the 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, to undertake some of these practices. 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 are using 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 the ability to reach our estimated potential. These findings will be incorporated into future modeling efforts.

Finally, we offer two closing thoughts in light of this initial study. First, it is clear that 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. Second, most of these NCSs have important contributions to make to the urgent need to reduce greenhouse gas concentrations in the atmosphere, and at the same time they typically provide vital co-benefits that are often lumped into a term like ecosystem services. It should be noted, however, that most but not all are finite. We can increase carbon in forests and soils up to a point, but not forever. That makes their contributions between now and mid-century most critical for investment.

# Appendix A. Detailed Results

*Table 12. Maine forest NCS estimates for core (medium) analysis, 20 and 50-year means.*

| Scenario | Total Carbon Above Baseline (t$CO_2$e/yr) | Harvest Volume (gt/yr) | Mitigation Cost ($/yr) | Break-even Carbon Price ($/t$CO_2$e) |
|---|---|---|---|---|
| *20 Year Mean (2020-2040)* | | | | |
| BAU age (min 50) | 0 | 9,218,608 | $0 | $0 |
| Min 85 years | 977,442 | 8,293,587 | $12,288,424 | $14 |
| Min 100 years | 3,731,440 | 5,034,894 | $55,578,455 | $15 |
| 35% Clearcut (CC) | 322,382 | 8,758,310 | $6,114,819 | $2 |
| 50% Clearcut (CC) | 904,263 | 8,042,478 | $15,624,267 | $19 |
| 35% CC, plant | 2,094,584 | 8,752,861 | $29,847,046 | $15 |
| 50% CC, plant | 3,255,452 | 8,046,626 | $47,118,239 | $15 |
| 10% set-aside | 592,715 | 8,532,867 | $9,109,711 | $15 |
| 20% set-aside | 1,370,633 | 7,631,017 | $21,090,314 | $15 |
| 35% CC, plant, 10% set aside | 2,536,070 | 8,103,470 | $36,888,130 | $15 |
| 35% CC, plant, 20% set aside | 3,121,529 | 7,240,923 | $31,400,585 | $15 |
| Afforestation | 735,443 | 9,218,608 | $22,063,299 | $30 |
| Avoided Conversion - Crop | 100,086 | 9,218,608 | $2,058,912 | $21 |
| Avoided Conversion - Developed | 341,358 | 9,218,608 | $239,925,645 | $703 |
| *50 yr mean (2020-2070)* | | | | |
| BAU age (min 50) | 0 | 9,332,668 | $0 | $0 |
| Min 85 years | -18,276 | 9,475,356 | -$1,895,530 | $15 |
| Min 100 years | 830,094 | 8,115,025 | $16,175,762 | $12 |
| 35% Clearcut (CC) | -69,900 | 9,291,435 | $547,764 | $6 |
| 50% Clearcut (CC) | 165,926 | 8,887,980 | $5,907,455 | $11 |
| 35% CC, plant | 2,453,073 | 9,301,018 | $24,080,330 | $11 |
| 50% CC, plant | 3,516,260 | 8,911,726 | $37,139,123 | $11 |
| 10% set-aside | 493,224 | 8,654,385 | $9,010,648 | $20 |
| 20% set-aside | 1,159,547 | 7,728,575 | $21,309,545 | $20 |
| 35% CC, plant, 10% set aside | 2,766,020 | 8,630,582 | $31,400,585 | $12 |
| 35% CC, plant, 20% set aside | 3,195,906 | 7,708,553 | $41,327,285 | $13 |
| Afforestation | 759,617 | 9,332,668 | $22,788,513 | $30 |
| Avoided Conversion - Crop | 200,155 | 9,332,668 | $4,117,478 | $21 |
| Avoided Conversion - Developed | 685,428 | 9,332,668 | $481,757,790 | $703 |

*Table 13. Maine agricultural NCS estimates by sensitivity case*

| **NCS Practice** | **Total Mitigation ($tCO_2e$/yr)** | **Total Cost (Mil $/yr)** | | | **Break-Even Price ($/$tCO_2e$)** | | |
|---|---|---|---|---|---|---|---|
| | **Medium** | **Low** | **Medium** | **High** | **Low** | **Medium** | **High** |
| No-till from Intensive | 32,755 | $1.70 | $2.96 | $4.22 | $52 | $90 | $129 |
| No-till from Reduced | 13,994 | $2.21 | $2.36 | $2.50 | $158 | $168 | $178 |
| Reduced tillage | 13,423 | -$1.91 | $2.34 | $7.15 | -$142 | $174 | $532 |
| Cover Crops | 24,161 | $6.80 | $10.48 | $13.28 | $281 | $434 | $549 |
| Biochar | 568,898 | $10.86 | $14.48 | $28.96 | $19 | $25 | $51 |
| Amend w/ Manure | 55,112 | $0.81 | $4.85 | $6.44 | $15 | $88 | $117 |
| Convert to Perennial | 406,022 | $7.97 | $12.38 | $21.24 | $20 | $30 | $52 |
| Riparian Buffer | 39,805 | $3.41 | $4.57 | $5.73 | $86 | $115 | $144 |
| Dairy Manure Mgmt | 144,132 | $1.42 | $4.33 | $8.14 | $10 | $30 | $56 |

# Appendix B. Detailed Input Data

## Maine forest systems

*Table 14. 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 1 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 15. 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 (*2017 Census of Agriculture*, 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 is partly based on USDA's Agricultural Resource Management Survey (*Commodity Costs and Returns*, 2020).

Table *16* summarizes the key revenues and costs for a typical Maine barley cropping system.

*Table 16. 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 but 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 1,000 lbs/acre) (Files et al., 2008) to lower pH and manage weeds, application of herbicides, fungicides, and insecticides, and irrigation on an as-needed basis 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 1970's, 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.”[19] However, use of organic mulches including living mulches, as well as use of cover crops in lowbush blueberry systems, represent areas of theoretical promise in which new research is currently being conducted.[20]

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 17 summarizes the key revenues and costs for a typical Maine blueberry cropping system.

*Table 17. 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 | $2,198 | $38 | $0.01 |
| Disease Control | $4,099 | $71 | $0.02 |
| Irrigation | $0 | $0 | $0.00 |
| Sulfur (pH) | $0 | $0 | $0.00 |
| Harvest (raking and mechanical) | $36,711 | $632 | $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** | **$87,315** | $1,504 | **$0.34** |
| **Total Costs** | **$87,315** | **$1,504** | **$0.34** |
| **Net Revenue** | **$34,709** | **$598** | **$0.13** |

[19] D. Yarborough, personal communication, January 27, 2020.
[20] 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 (*2017 Census of Agriculture*, 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.[21] 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 18 summarizes the key revenues and costs for a typical Maine silage corn cropping system.

*Table 18. Silage 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.

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

Overall a mature dairy cow 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 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 19 summarizes the key revenues and costs for a typical Maine dairy cropping system.

*Table 19. 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, left to its own devices, 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 20 summarizes the key revenues and costs for a typical Maine hayfield cropping system.

*Table 20. 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** |

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 what 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.[22] Most growers are using a 1:1 rotation with one year of potatoes and one year of a much less valuable cash crop like a grain or an unharvested cover crop. Some growers are using a 2:1 rotation with a longer “off” period from potatoes.[23] 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.[24] Soils are also generally uncovered and susceptible after potato harvest, as well as following fall tillage in the preceding rotation crop.[25]. The multiple tillage/cultivation passes inherent to potato planting and hilling are harmful for soil organic matter and aggregation (i.e., good soil

[22] J. Jemison personal communication, February 2018.

[23] N. Lounsbury, unpublished data, January 23, 2020.

[24] J. Jemison personal communication, February 2018.

[25] Lounsbury, unpublished data, January 23, 2020.

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 corn in rotation. Table 21 summarizes the key revenues and costs for a typical Maine potato cropping system.

*Table 21. Potato Farm Budget.*

| | **Revenue** | | |
|---|---|---|---|
| | Potato (cwt) | Corn (bu) | |
| Number of acres | 160 | 160 | |
| Yield/acre | 240 | 100 | |
| Yield | 38400 | 8960 | |
| Unit Price | $10.46 | $3.69 | |
| Annual Revenue | 401664 | 33044.48 | |
| | Total | Per Acre | Per Cwt |
| | **Variable Costs** | | |
| Seed | $57,463 | $179.57 | $1.21 |
| Fertilizer | $45,534 | $142.29 | $0.96 |
| Lime | $4,884 | $15.26 | $0.10 |
| Chemicals | $41,711 | $130.35 | $0.88 |
| Labor | $58,728 | $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** | **$331,156.06** | **$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** | **$111,031.38** | **$346.97** | **$1.70** |
| **Total Annual Cost** | **$442,187.44** | **$1,381.84** | **$8.69** |
| **Net Farm Income (NFI)** | **$18,484.56** | **$57.76** | **$1.03** |
| **Return over Variable Cost** | **$129,515.94** | **$404.74** | **$2.73** |

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 (*2017 Census of Agriculture*, 2019). The crops are grown in five hundred 100-foot rows. Table 22 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,[26] 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 22. Diversified vegetable farm budget.*

| Cost Component | Mean Veg (100-ft row) | Total Veg part of farm (500 rows) | Total/veg ac |
|---|---|---|---|
| **Revenue** | $442.35 | **$221,174** | **$ 22,117.43** |
| Variable Costs | $234.48 | $117,238 | $ 11,723.78 |
| Fixed Costs | $111.05 | $55,524 | $ 5,552.38 |
| **Mixed Veg Total Costs** | $345.52 | **$172,762** | **$ 17,276.16** |
| **Return over variable costs** | $207.87 | **$103,936** | **$ 10,393.64** |
| **Return over total costs** | $96.83 | **$48,413** | **$ 4,841.26** |

***Wheat***

According to the 2017 USDA NASS Census of Agriculture, 262 acres of winter wheat were grown in Maine (*2017 Census of Agriculture*, 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 23* summarizes the key revenues and costs for a typical Maine wheat cropping system.

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

*Table 23. 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 |
| | | 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 24 and 25. Additional input assumptions that we applied for the dairy manure management practices are listed in Table 26. Information and literature reviews concerning NCS practices and their applicability to growing systems in Maine is contained in the following sections of text corresponding to each included NCS practice and cropping system.

*Table 24. 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[27] | 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[28] | 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. |

[27] 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). *Estimating Manure Application Rates* [University]. Penn State Extension. https://extension.psu.edu/estimating-manure-application-rates
[28] Assuming a one-time application of 5.9 Mg / ac with benefits for 20 years

*Table 25. 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[29] |
| **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[30] |
| | 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 |

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

[30] 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 26. 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 (t$CO_2$e/yr) | 16,000 | 2,097 | 8,162 | 1,920 | 2,883 |
| GHG mitigated per cow (t$CO_2$e/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,[31] and distribution of crop and other plant residue 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, 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 includes 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 (*2017 Census of Agriculture*, 2019). As a result, additional inference may need to be made to allocate tillage practices to the other 68% of cropland in the state, of which most could be no till (e.g., blueberries, hay, etc.).

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

***Reduced-till cropping (RT)***

Reduced-till practice manages the amount, orientation, and distribution of crop and other plant residue 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 includes 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 (*2017 Census of Agriculture*, 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 (*2017 Census of Agriculture*, 2019).

***Biochar Amendments***

Biochar is a substance similar to charcoal, which can be used as a soil or growing media amendment. It is typically produced from biomass using pyrolysis technology where oxygen is either absent or depleted (K. 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 the 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, are not expected in for our 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 Mg $ha^{-1}$ would sequester 0.85 Mg C $ha^{-1}$ $year^{-1}$.[32] This value is in line with prior literature, which indicates a broad range of sequestration values from 0.2 to 5.3 Mg C $ha^{-1}$ $year^{-1}$ (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 to consider 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.[33]

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

[32] P. Ciborwski, personal communication, June 16, 2020.
[33] J. Jemison, personal communication, Spring 2020.

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 includes 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 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 and diminish herbicide 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 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 as anaerobic digester for manure management, the Fogler Dairy Farm in Exeter (*Stonyvale Farm (Fogler Farm) Anaeorobic Digester System*, n.d.). 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 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 nitrous oxide emissions (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 increase 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 phosphorous 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 makes timing manure application to coincide with plant fertility needs a challenge. 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 fertility 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 perhaps 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, and 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 (*2017 Census of Agriculture*, 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 this 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 water borne pathogens/nutrients. It has similar vegetation as Zone 1 as it is mostly 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 agriculture and commercial tree 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 should consist 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 implement riparian buffers include planting, maintenance, and opportunity costs. Agricultural land directly adjacent to waterways is often less productive then 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 (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 27.

*Table 27. 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 | $248.45 |
| Annual Average Carbon Sequestration (t$CO_2$e/ac/yr) | 1.23 | 1.69 | 2.13 |
| Break Even Carbon Price ($/t$CO_2$e) | $114 | $115 | $117 |

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

*Table 28. Range of agricultural NCS GHG mitigation factors from literature (tCO2e/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 US 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 2010-2070 (Figure 20). It is important to note that using this process, implicitly assumes no change in forest management on commercial forestlands outside our project study area, nor accounts for the potential effects of climate change on forest productivity.

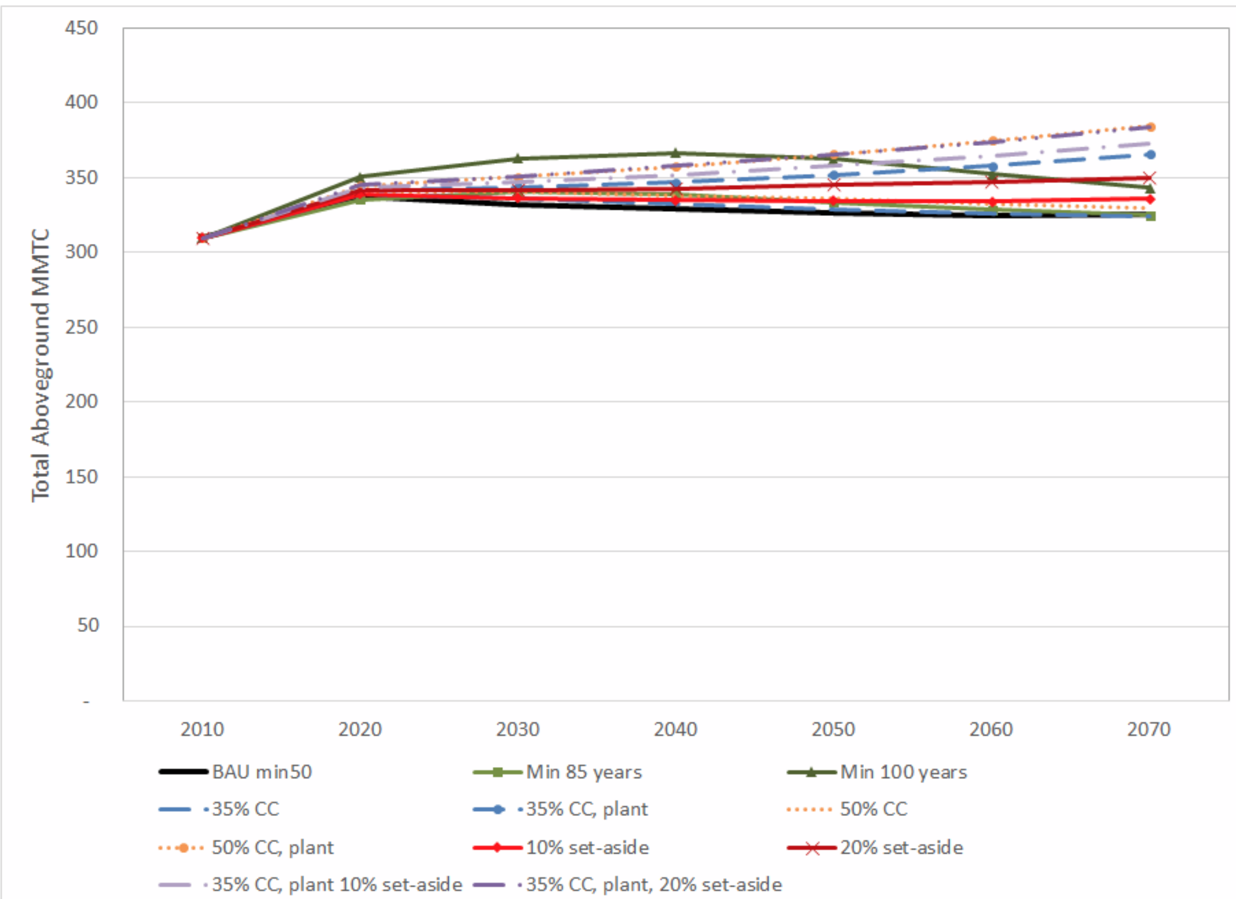


*Figure 20. Total forest carbon stock (MMTC) for all of Maine, including 7.5 million acres outside of the Landis model study area, modeled from 2010 to 2070.*

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