Photo: Johnny Sanchez

An Issue Analysis of Soil Carbon Sequestration and Storage in Maine

Report to the Joint Standing Committee on Agriculture, Conservation and Forestry

September 1, 2022

Acknowledgements

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Table of Contents

Executive Summary

This project seeks to assist Maine policy makers in addressing climate change by developing recommendations for programs and policies to improve soil carbon storage, as outlined in LD 937. The management practices farmers, foresters, and other land managers choose to apply on natural and working lands have substantial ramifications for sequestration (a rate) and storage (a stock) of soil carbon. These represent important opportunities for climate change mitigation in Maine because additional carbon stored in ecosystems means less carbon in the atmosphere. This report outlines recommendations that can inform programs and policies on this issue. This report includes: (1) a review of findings primarily from the peer-reviewed scientific literature pertaining to management practices that enhance soil carbon in agricultural, forest, and wetland systems; (2) an assessment of soil carbon monitoring capacities needed to inform science-based policy; and (3) a summary of policies and incentives in other states that could inform soil carbon policy development in Maine.

Introduction

About LD 937

This legislation, signed by Governor Janet Mills on June 8, 2021 as Chapter 28 of the Resolves of 2021, directed the Maine Department of Agriculture, Conservation and Forestry (DACF) and the Department of Inland Fisheries and Wildlife (DIFW) to jointly develop recommendations regarding carbon storage programs and policies for the state of Maine. Specifically, the Departments were charged with developing recommendations for the establishment of "*programs and policies to promote and incentivize, where appropriate, practices that increase sequestration of soil carbon on natural and working lands by farmers, landowners and land managers, including, but not limited to, technical assistance and financial incentives for that purpose.*" These objectives are consistent with the goals of Maine's climate action plan *Maine Won't Wait.* This can be achieved by the development of programs and policies that may aid in climate mitigation and resilience by promoting and incentivizing, where appropriate, practices that increase sequestration of soil carbon (the net rate of carbon uptake into soils) and the storage (the total stock of carbon in soil at a given time) on natural and working lands by farmers, landowners, and land managers.

The Resolve became effective October 18, 2021, and the Departments met several times to develop a scope of work for the study. The Governor's Office of Policy Innovation and the Future (GOPIF) initiated a request to the United States Climate Alliance (USCA) for technical assistance. USCA has provided a technical assistance award to DACF for facilitation services and scientific and technical support for the project. The timeline outlined in the Resolve required delivery of an interim report with findings and recommendations by March 1, 2022 to the Joint Standing Committee on Agriculture, Conservation and Forestry which was delivered on time, followed by submission of this final report on or before September 1, 2022.

Purpose and Scope of Report

DACF and DIFW worked with the University of Maine to provide scientific and technical support to the Departments for this study. The project aimed to develop background information in support of recommendations for programs and policies that provide natural and working land stakeholders with incentives to improve soil carbon storage, either by preventing soil carbon loss or increasing soil carbon sequestration. Specific objectives of the study included:

1. Conduct a scientific and technical literature review of existing relevant management practices that enhance soil carbon, with preference given to studies that are conducted in the glaciated Northeast or comparable regions.
2. Explore research and monitoring needs; identify important gaps in knowledge where more research is needed.
3. Identify existing programs, policies, and incentives in other states that could serve as a template or proof-of-concept for similar programs in Maine.

This report summarizes completed work addressing these three specific objectives. The purpose of this report is to provide the Departments and policymakers with pertinent scientific and technical information to help inform further policymaking efforts.

About Soil and Soil Carbon

Soil is a widely under-appreciated, complex substance that is essential to human and environmental health as we understand it (Kopittke et al. 2022). Key components of soil include a variety of solids, water, air, and a community of organisms relying on one another for survival and interacting as components of an interdependent system (**Figure 1**). Energy enters the soil system via photosynthesis, through which the sun's energy is leveraged to take carbon dioxide from the atmosphere and add it to the living bodies of plants, both above and below ground. When plants and the animals that ingest them (up the food chain) die and their bodies decay, much of the carbon in their tissues - especially those present in plant roots - remains in the soil system in changing forms, becoming soil organic matter that feeds microscopic life through a complex set of chemical and biological processes.

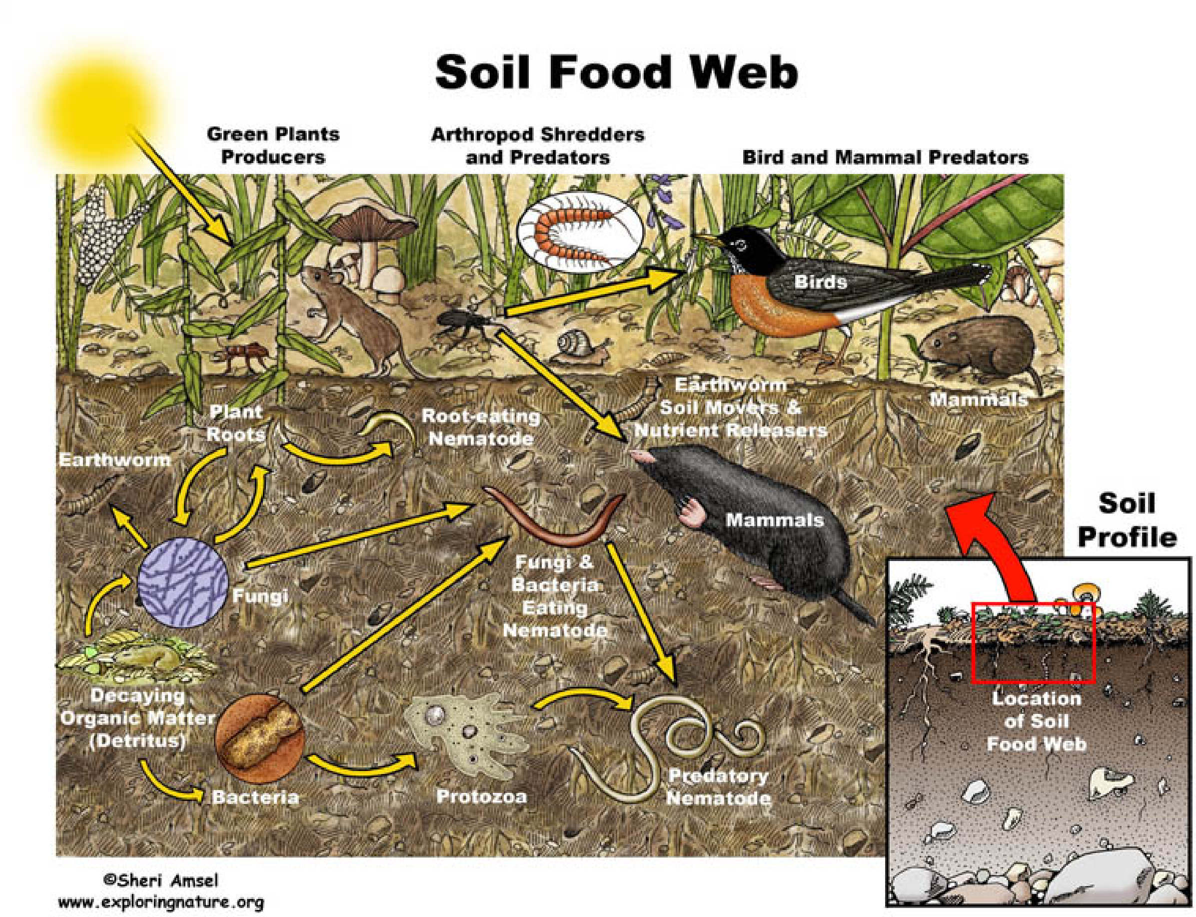

Figure 1: Diagram illustrating many typical biotic (living) components of Maine soils, and some of the complex ways they interact as an interdependent food web.

At the ecosystem scale, soil is deeply integrated into biogeochemical processes foundational to life on earth. Some of the key functions of soil on which we depend include support for food and fiber (biomass) production, regulation of carbon, nutrient cycling, biodiversity, and water purification and cycling (**Figure 2**).

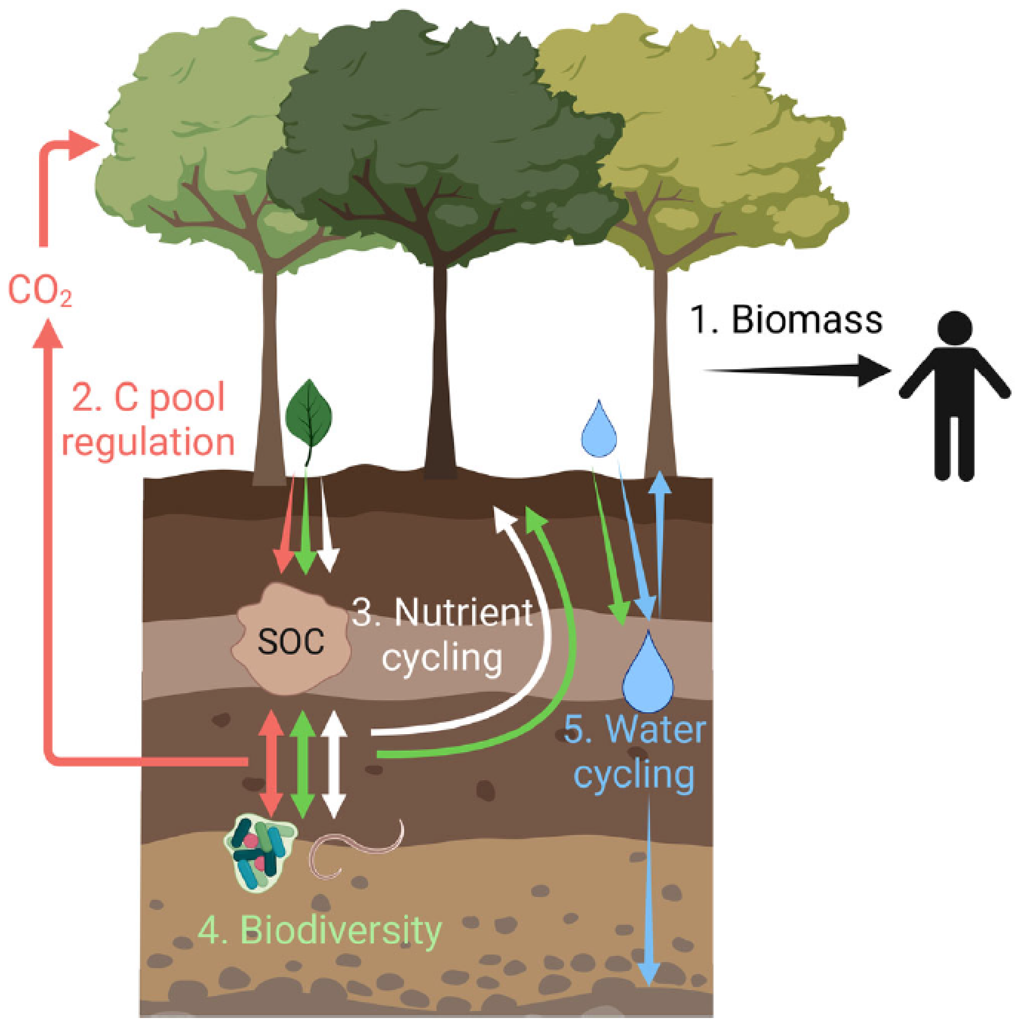

Figure 2: Diagram illustrating five key functions of soil (From: Kopittke et al. 2022).

The function of soil most directly relevant to this study is carbon pool regulation. Soil carbon can include both inorganic and organic forms of carbon (the latter of which is often called soil organic carbon or SOC). Although SOC is a term used primarily in scientific contexts, many gardeners will be familiar with the related term soil organic matter, which in a farm or garden setting is a benchmark for soil health. SOC is simply the portion of soil organic matter that is made up of the element carbon - generally upwards of 50%. Organic matter and its SOC contribute substantially to soil health benefits that include improvements to the water-holding capacity and structural stability of soils, which in turn increases resilience to moisture extremes and, in a variety of direct and indirect ways, supports plant growth and provides food and habitat for other beneficial soil organisms. The focus of potential new management opportunities for soil carbon related to climate change mitigation and resilience here is on SOC, and not inorganic carbon found in carbonate rocks and minerals in soils and their parent materials.

Soil carbon has clear linkages to atmospheric greenhouse gas concentrations. Carbon atoms trapped in soils as inorganic or SOC are *de facto* not present in the atmosphere as greenhouse gasses such as carbon dioxide and methane (Oertel et al. 2016). Given the ubiquity of soils worldwide, soil carbon pools represent a crucial buffer against anthropogenic climate change, storing more organic carbon than the atmosphere and all the vegetation on earth combined, and providing an economic value estimated at $3.5 trillion annually on a worldwide scale (Jónsson & Davıðsdottir 2016; Kopittke et al. 2022)

Soil carbon stores are not only vast, they are also dynamic. An estimated 7% of the atmospheric carbon pool cycles through soils annually through a variety of processes (Lehmann & Kleber 2015). Land management practices greatly impact SOC pools, and represent key opportunities for climate change mitigation. When considering the complex interactions between climate, SOC, and land management, it can be useful to divide management actions into two broad categories: (1) those aimed at conserving SOC stocks already present in soils, and (2) those aimed at restoring or adding to existing stocks.

As is clear from **Figure 3**, there are considerable carbon stocks already present in Maine soils, and especially forest soils. Many land management practices relevant to agriculture, forestry, and wetlands can impact carbon “fluxes” - either additions to or subtractions from - SOC stocks. The literature review below provides an initial overview of relevant management practices that can conserve or add to SOC stocks in Maine natural and working lands.

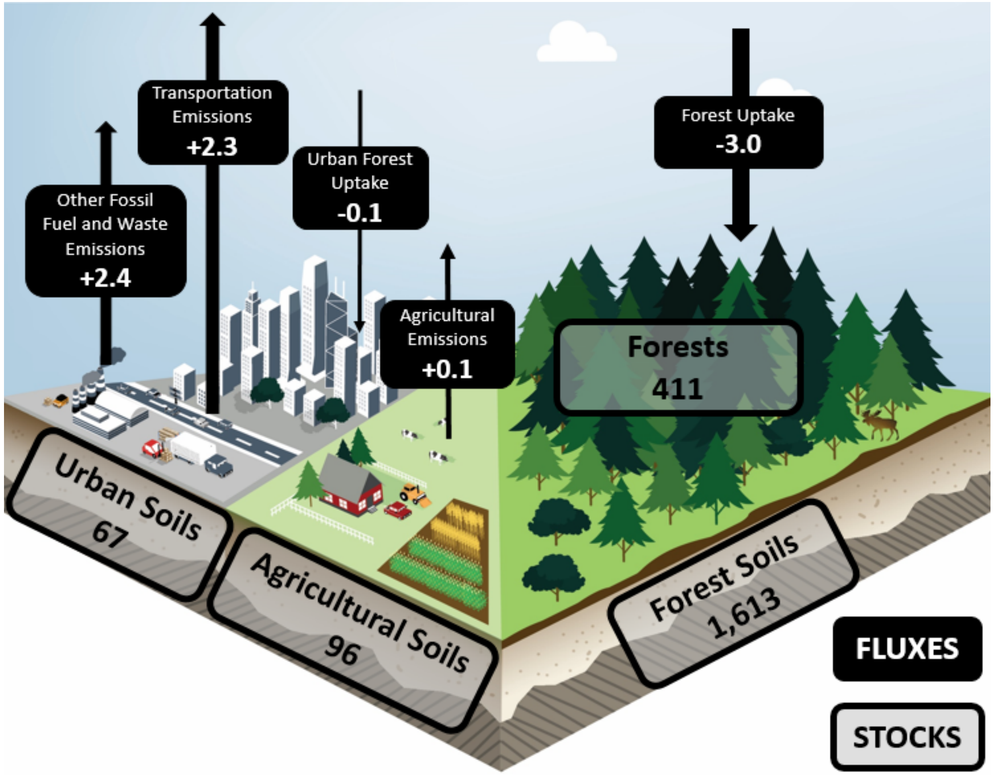

Figure 3: A summary diagram showing soil carbon stocks in forest, agricultural, and urban soils in Maine, and important processes through which carbon moves (fluxes) between these soils and the atmosphere (From: The State of Maine Carbon Budget, Version 1.0; data shown in million metric tons of carbon or MMTC).

Literature Review

The following literature review aims to present a concise and applications-focused summary of scholarly literature relevant to the three major objectives outlined in the "Purpose and Scope of Report" section above: soil carbon management practices for natural and working lands in Maine, soil carbon monitoring and research needs, and existing soil carbon policies and programs in the United States.

1. Soil Carbon Management Practices for Natural and Working Lands

1.1 Agriculture

Overall, there exists a large body of literature relating to the role of agricultural management practices on soil carbon stores, including many excellent syntheses and meta-analyses (Bai et al. 2019; Griscom et al. 2017; Jian et al. 2020; Paustian et al. 2016; Paustian, Larson et al. 2019). The following is a summary of key findings and considerations relevant to management practices impacting carbon pools in agricultural systems.

1.1.1 Soil Carbon Dynamics in Agricultural Systems

Increasing stores of carbon in agricultural soils acts to mitigate the amount of carbon in the atmosphere and to maintain or improve crop productivity by positively contributing to soil health. Land conversion from natural ecosystems to agricultural systems typically depletes SOC stocks due to factors including lower carbon inputs from plant biomass, increased erosion and leaching, accelerated decomposition of organic matter, and stronger variation in soil moisture and temperature (Lal et al. 2015). Conversely, existing croplands often have significant potential for increased soil conservation and SOC sequestration. If strategically managed using context-appropriate best practices, croplands that were previously net sources of carbon dioxide emissions can transition to becoming carbon sinks (Lal et al. 2018). Although there are practical ceilings for the amount of SOC that can be stored in soils, many degraded agricultural soils have the potential for ongoing soil health improvement and accelerated SOC sequestration over the next two to three decades before reaching equilibria at which the rates of further improvement slow over time (Paustian et al. 2016).

Two main factors influence the effectiveness of practices aimed at sequestering and storing carbon in agricultural systems: (1) the productivity of the system, and (2) the length of time carbon is stored in the soil, also known as the mean residence time (Lal et al. 2018). Because the efficacy of individual practices is context-dependent, there is no one-size-fits-all best management practice for improving SOC storage capacity. However, success across a range of contexts can be achieved by thoughtfully applying the following general soil health principles:

1. Continuous, year-round soil cover using crop residues, mulch, and cover cropping;
2. Applying integrated nutrient management to replace nutrients lost through crop harvest;
3. Improving soil structure; and
4. Reducing SOC losses from erosion, volatilization, or leaching.

Applying these principles while choosing specific practices appropriate to an individual farmers' context is proposed as a widely-applicable best practice framework (Lal et al. 2018).

1.1.2 Management Practices to Increase Carbon Storage and Sequestration

Management practices that store carbon in agricultural soils rely on either increasing SOC or reducing loss of SOC already present (Paustian, Larson et al. 2019). Practices that may increase SOC include use of natural mulches, cover crops, and additions of organic amendments including manure and biochar. Practices that minimize soil disturbance help to conserve as well as add SOC to the system. Key practices fitting this latter description include no-till and reduced-tillage cropping practices, and conversion of land from annual to perennial crop production. *Critical to conserving existing SOC is the avoidance of the loss of agricultural soils to development.*

Agricultural practices that contribute to SOC sequestration and storage are often grouped together under related umbrellas of climate-smart farming (Paustian et al. 2016), conservation agriculture (Bai et al. 2019), regenerative agriculture (Lal 2020), and natural climate solutions (Griscom et al. 2017). Each of these suites of practices are further described below.

Climate-smart farming broadly defined is an integrated approach to the interlinked challenges of providing for food security while addressing climate change (Lipper et al. 2014). This may include practices that increase climate resilience through mitigation and adaptation to climate impacts. Climate-smart management practices that increase SOC inputs (**Figure 4;** Paustian et al. 2016) include:

1. Choosing crop varieties or species with greater root mass, depositing more carbon in soils and in deeper soil layers thereby increasing its mean residence time in the soil;
2. Choosing crop rotations that provide greater carbon inputs;
3. Increasing crop residue retention;
4. Providing continuous carbon inputs by cover cropping during fallow periods;
5. Reducing tillage intensity or no-till;
6. Transitioning from annual to perennial crops;
7. Adopting optimal grazing densities in grasslands;
8. Using irrigation in water-limited systems;
9. Increasing fertilizer inputs in nutrient-deficient systems to improve productivity; and
10. Applying external carbon inputs such as compost or biochar.

Other climate-smart practices could include monitoring and mitigating the use of chemical inputs that produce greenhouse gas emissions, such as the herbicide glyphosate (Lal 2004a).

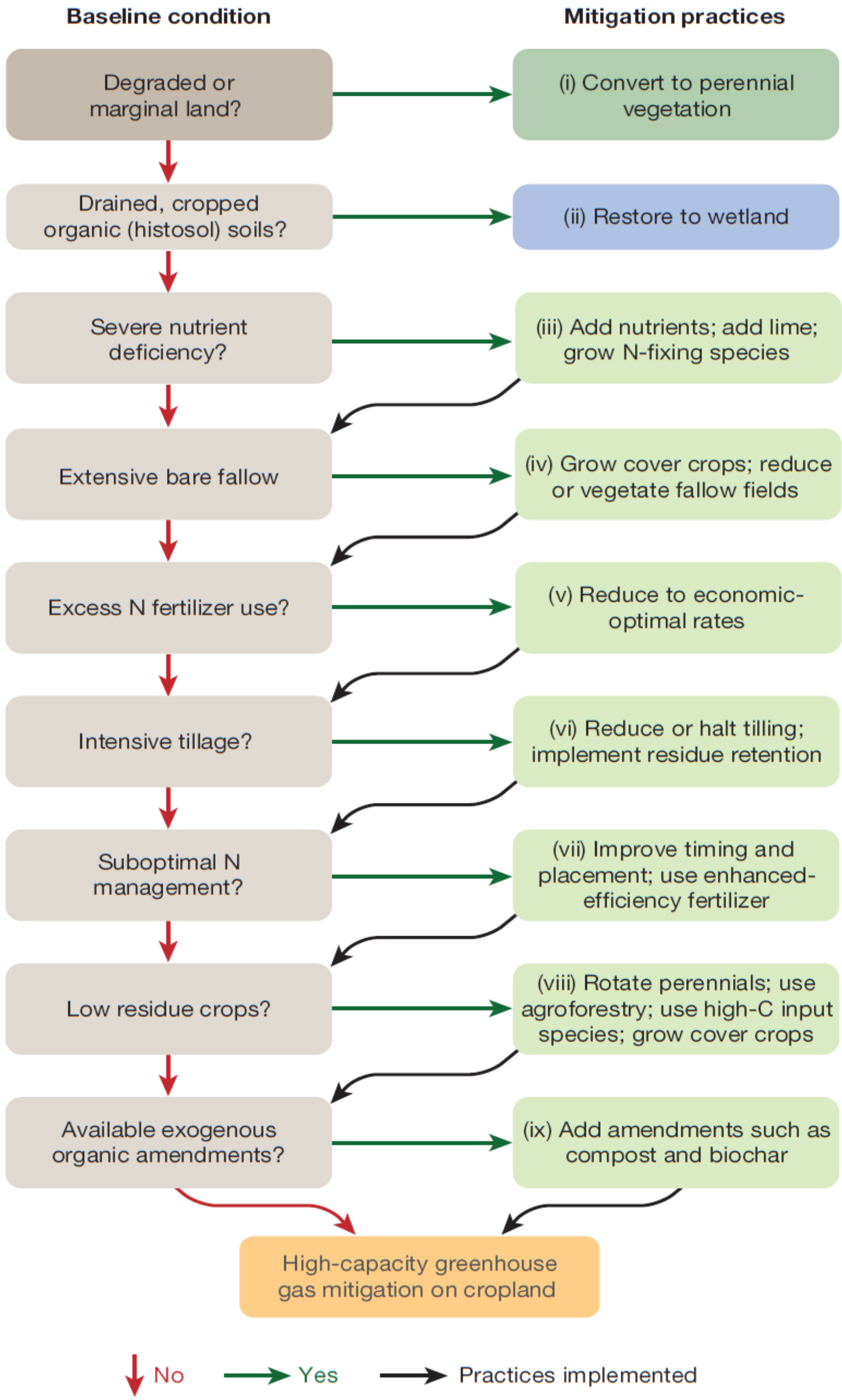

Figure 4. Decision tree for implementing climate-smart farming practices based on farm conditions (From: Paustian et al. 2016).

Conservation agriculture is a farming system that promotes minimal soil disturbance, maintenance of a permanent soil cover, and diversification of plant species (Lal 2015). Conservation agriculture includes a smaller set of practices than climate-smart farming, with an emphasis on practices that can be integrated into no-till systems. Through increased biodiversity and improved soil structure over time, conservation agriculture can increase water and nutrient use efficiency and lead to sustained improvements in crop production (Bai et al. 2019; Lal 2015).

Regenerative agriculture is a suite of crop and livestock management practices that seeks to reverse land degradation and climate change by rebuilding soil health, contributing to SOC sequestration and storage (Lal 2020). Many of the practices involved overlap with climate-smart and conservation agriculture practices. In a series of regenerative agriculture simulations of Vermont farmland, models predicted that converting all farmland to rotational grazing would increase SOC sequestration by 15% after 100 years, surpassing a 6.6% increase over the same time frame from tilled cropland with regenerative best management practices, including cover crops (Wiltshire & Beckage 2022). However, models showed that conventionally-managed continuous pasture was only predicted to increase SOC sequestration by 4.2% over 100 years, suggesting that intensive rotational grazing is key to achieving higher sequestration of SOC (Wiltshire & Beckage 2022).

Natural climate solutions are a suite of land stewardship practices meant to build carbon storage or reduce greenhouse gas emissions; in agricultural settings, these include the practices of biochar application, incorporating trees in croplands, nutrient management, grazing management, and avoiding the conversion of grasslands (Griscom et al. 2017). Many of these practices, again, overlap with the umbrellas of climate-smart, conservation, and regenerative agriculture already discussed. A recent analysis of natural climate solutions relevant to Maine agriculture and forestry suggests that biochar and conversion to perennial crops were theoretically among the most cost-effective of the practices considered for the specific goal of SOC sequestration and storage (**Figure 5**). Their analysis did not attempt to incorporate a broader range of socio-economic factors that influence farmer decision-making. Biochar is a charcoal-like organic material created by burning biomass, such as crop residues, wood chips, or manure, in environments with little-to-no oxygen. This process chemically converts the carbon stored in biomass into a stable form that cannot be easily converted back to CO_2 by microbial decomposition and released into the atmosphere, which normally occurs as plant or animal materials decompose in the soil. Biochar acts to sequester carbon and has been suggested as a carbon dioxide removal (CDR) technology (Schmidt et al. 2021). Further discussion of biochar application as a practice is included below. Although biochar utilization in agriculture is a growing practice globally, biochar application is not widely practiced in Maine at present (Birthisel et al. unpublished data; Daigneault et al. 2021).

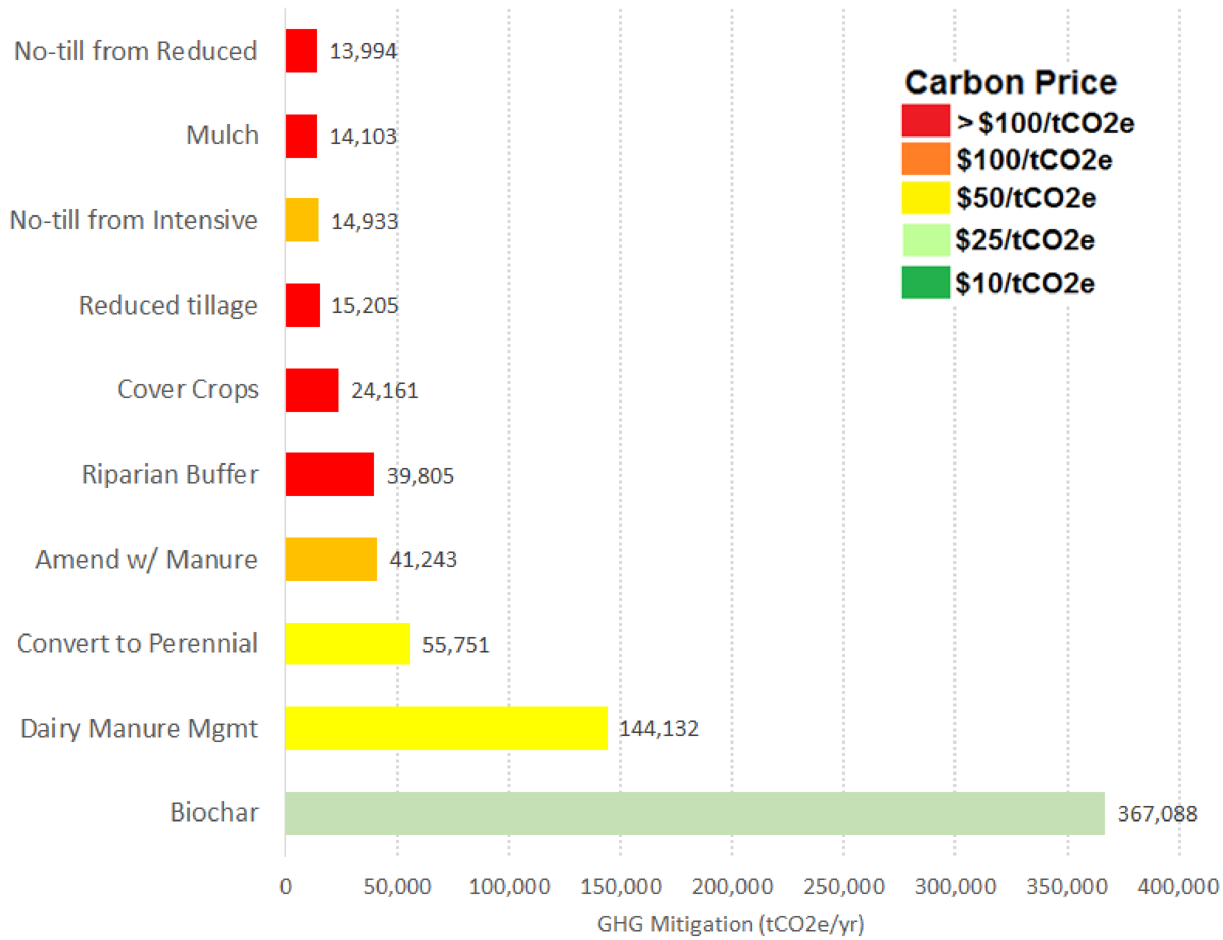

Figure 5. Total greenhouse gas mitigation potential and estimated carbon price of several ‘natural climate solutions’ estimated for agricultural land in Maine. Practices shown here that are relevant to soil organic carbon sequestration and storage include: no-till, mulch, reduced tillage, cover crops, conversion to perennials, and biochar (From: Daigneault et al. 2021).

Of specific practices proposed for increasing or retaining SOC stores in agricultural soils, cover cropping and reduced tillage have appeared most often in the literature reviewed through this project (e.g., Bai et al. 2019; Bruner et al. 2020; Hopwood et al. 2021; Jian et al. 2020; Lal 2004b; Lal et al. 2015; Paustian et al. 2016), and warrant some additional notes regarding their optimal application for SOC sequestration and storage. Additional literature review pertaining to biochar is also included, due to the high theoretical potential of this practice for carbon sequestration and storage in Maine (**Figure 5**).

Cover crops are plants grown for the purpose of soil protection or improvement rather than for harvest as "cash crops." Changes in SOC vary with cover crop type; leguminous cover crops have been shown to increase SOC more than grasses (Jian et al. 2020) and non-legume species (Bai et al. 2019). Cover crops that include strategic mixtures of plant species can increase SOC more than single species cover crops (Jian et al. 2020). The manner in which cover crops are managed also matters: cover crops enhanced SOC storage by 6% when crop residues were returned to the soil, but did not result in increased SOC when crop residues were removed (Bai et al. 2019). Cover crops also have many agronomic benefits beyond increasing SOC, including reducing runoff and erosion, increased mineralizable carbon, and increasing mineralizable nitrogen and soil nitrogen (Jian et al. 2020).

In a recent meta-analysis, *conservation tillage* including no-till and reduced tillage was found to increase SOC storage by 5% overall, with similar effects for no-till vs. reduced tillage. However, reduced tillage only increased SOC if crop residues were returned to the soil (Bai et al. 2019). In a study comparing conventional tillage with no-till and low, medium, and high levels of corn residue mulching, no-till with medium mulching offered the best trade-off between level of inputs and improving SOC storage (Yang, Xie et al. 2022). No-till practices may also affect SOC by influencing the levels of fungal and microbial biomass within the soil (Yang, Xie et al. 2022). Reduced tillage, no-till, and cover crop practices are well-established pillars of existing soil health programs and represent win-win best practices for carbon sequestration and storage as well as overall agroecosystem health, with potentially even greater benefits when these practices are applied together (Bai et al. 2019; Wolff et al. 2018).

Biochar can have positive effects on soil physical and chemical properties, soil microbial activities, plant biomass and yield, and potential greenhouse gas emission reductions (Hui 2021). Several studies have noted that biochar applications have some of the highest potential for soil carbon sequestration among relevant agricultural practices, including cover cropping and reduced tillage (Bai et al. 2019; Griscom et al. 2017; Paustian et al. 2016). However, there are many unknowns about this practice that should be addressed through field and laboratory research to verify promising theoretical results before appropriate policy mechanisms can be developed to support adoption of this practice. While biochar can provide agronomic co-benefits (Schmidt et al. 2021), at the global scale, practices such as nutrient management and agroforestry may be more cost-effective for farmers depending on the context (Griscom et al. 2017). Agroforestry is gaining increased attention as part of the focus on the role of ecosystems in sequestering SOC. The USDA defines agroforestry as *the the intentional integration of trees and shrubs into crop and animal farming systems to create environmental, economic, and social benefits. It has been practiced in the United States and around the world for centuries.* Silvopasture is a closely related term that focuses on integrating trees with grazing livestock operations providing income streams from both operations over time.

It is important to note that biochar is not a singular material, but represents a category of substances with widely varying composition depending on feedstock and production process (**Figure 6**). Considering the energy required to produce various sources of biomass will be necessary to more fully understand the potential of biochar to lead to net reductions in greenhouse gas emissions (Gaunt & Lehmann 2008). Net greenhouse gas reductions that offset the potential energy released from burning biochar are best achieved if 1) the biochar applied reduces soil greenhouse gas emissions other than the carbon in the biochar, such as methane, or 2) if the application increases plant growth for future biochar production, SOC accumulation, or both (Lal et al. 2018). The estimated global life-cycle potential of carbon sequestration from biochar is 0.5 to 1.1 Pg C per year, including both above- and belowground carbon storage (Lal et al. 2018). The application of raw biochar to soil is considered impractical due to long financial payback times (15-125 years) and the potential for compounds to accumulate with uncertain effects on plants and soil microbes (Kochanek et al. 2022). It will also be increasingly important to characterize the biochar used, as there can be biochar produced as the primary product, and biochar byproducts of other commercial processes (Bai et al. 2022).

Improving the efficacy and wider applicability of biochar should involve (Kochanek et al. 2022):

1. Biochar standardization to avoid contaminants and improve the predictability of biochar effects;
2. Incorporating biochar into other profitable inputs, such as fertilizers, that provide additional benefits to plant and soil health; and
3. Adopting a circular economy approach to biochar production (**Figure 6**)

One simple and potentially helpful framework is a ‘3R principle’ for maximizing biochar benefits, including using the ‘right biochar source, right application rate and right placement in soil’ ([Kochanek et al. 2022](#)).

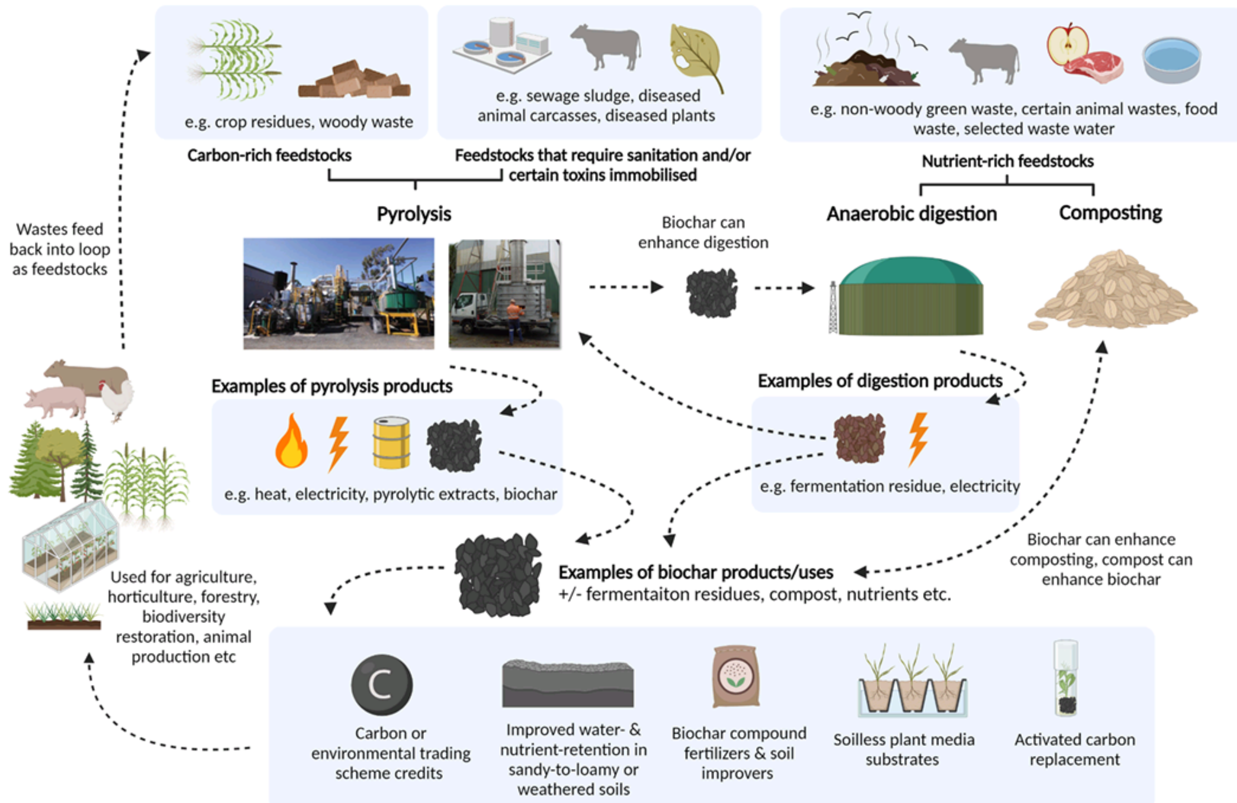

Figure 6. An example of a circular economy approach to producing and implementing biochar (From: [Kochanek et al. 2022](#)).

Many of the practices that store carbon in soils have additional benefits beyond building SOC. Keeping the soil covered through practices including cover cropping and reduced- or no-tillage can help reduce erosion and soil loss. Organic amendments like biochar and the incorporation of crop residues into the soil help build soil organic matter. Emphasizing the multiple benefits and win-win nature of many of these practices in future policy and program-building efforts could help improve practice adoption by farmers.

Finally, it is important to note that environmental factors can influence how effectively management practices sequester carbon. In a meta-analysis on climate-smart practices, cover-cropping, conservation tillage, and biochar application were more effective at sequestering carbon in arid rather than humid areas, with the greatest differences found in biochar efficacy (Bai et al. 2019). Sequestration varied under different temperature regimes, with greater sequestration rates from biochar in cooler climates, but higher rates from cover crops and conservation tillage in warmer climates (Bai et al. 2019). This underscores the importance of region-specific data collection and monitoring highlighted below in Section 2 of this report, as well as the utility frameworks emphasizing general soil-health principles that can be tailored to individual farmers' contexts over one-size-fits-all solutions (Lal et al. 2018). A recent assessment of the potential for climate change mitigation globally through regenerative farming took a stoichiometric approach to assessing how realistic various approaches might be in achieving SOC sequestration goals. The author evaluated a range of practices based on recent meta-analyses and calculations for the use of manures, fertilizers, irrigation, cover crops, biochar, ground silicates, and the impacts of rising CO_2 and global warming, concluding that only cover crops and possibly biochar appeared the most promising when evaluated at a more comprehensive systems level (Schlesinger 2022).

1.1.3 Directions for Future Research

Note: Future research directions regarding soil carbon management practices are included for each subsection on agriculture, forestry, and wetlands, but they exclude soil carbon monitoring and measurement information needs, which are discussed separately in ***Section 2****. In all of these ecosystems,* ***understanding how a changing climate will impact SOC dynamics and the benefits or limitations of management practices*** *is a priority research need.*

A considerable body of research has demonstrated the utility of soil-health building practices for carbon sequestration and storage, and can inform the development of policy to support and incentivize agricultural management practices that contribute to climate change mitigation through these mechanisms.

Further research will also be helpful in refining our understanding of best practices and their application over time. Some directions for future research in this area include:

- Further field experiments that investigate combinations of climate-smart practices across a variety of climate and geographic conditions, as well as improved models that incorporate field data to quantify potential soil carbon sequestration due to multiple combined climate-smart practices (Bai et al. 2019).

- Long-term field studies that investigate soil carbon dynamics at a range of soil depths in response to management activities (Jian et al. 2020)
- Modeling and simulation exercises with realistic scenarios of farmer decision-making, including varying degrees of behavior change or adoption of regenerative practices (Wiltshire & Beckage 2022)
- Identifying the effects of climate-smart practices on other greenhouse gas emissions, particularly N_2O and CH_4, that could influence the overall net benefits and climate mitigation potential of the practice (Paustian et al. 2016).
- A more precise and accurate understanding of biochar effects on soil carbon, including through large-scale, long-term field studies of soil and plant responses to biochar (Hui 2021), standardization of biochar analysis and characterization (Schmidt et al. 2021) and biochar life-cycle assessments, which take into account the greenhouse gas impacts from biochar production, alternative end uses, and interactions with other soil processes that affect greenhouse gas emissions (Paustian et al. 2016).
- Determining whether SOC losses from converting forests to agricultural land use can be reduced over the long-term by integrating both systems through silvopasture (Contosta et al. 2022).

1.2 Forestry

There is a less extensive scientific literature pertaining to forest management practices on SOC sequestration and stocks as compared with agriculture, though several excellent synthesis and meta-analysis papers have been written recently and can be particularly valuable to inform policymaking efforts (Devi 2021; James et al. 2021; James & Harrison 2016; Kaarakka et al. 2021; Mayer et al. 2020; Nave et al. 2010, 2019, 2021; Ontl et al. 2020). The limited body of research on this topic reflects the focus on aboveground forest carbon as influenced by forest management, the costs of forest SOC research given the extent and physical depth of the soil resource typically considered in whole forest ecosystem function, and the lower intensity of management per acre for forestry compared to agricultural cropland. The following is a high-level summary of some key findings and considerations relevant to management practices impacting carbon pools in forest systems based on the scientific literature.

1.2.1 Soil Carbon Dynamics in Forest Systems

The largest stores of forest carbon are found in the soil (Nave et al. 2019), including here in Maine (Fernandez 2008). Total carbon storage in Maine forests was estimated to be over 1.6 billion metric tons in 1995 - an average of 223,325 kg C ha^{-1} - with about 80% of the carbon found in the soil and forest floor (Birdsey & Lewis 2003). Mineral soils below the forest floor or O horizon store the largest stocks of SOC due to their larger mass (**Figure 7**), but SOC concentration - the percentage of the soil layer consisting of SOC - is highest in the shallow forest floor (Fernandez 2008). It is also important to note in evaluating ecosystem carbon data, like that shown in **Figure 7**, what soil depth was for a study and whether soil depth was limited by methodology (e.g., we sampled to X cm soil depth, we sampled to the top of the C horizon) or the physical limitation of the soil (i.e., bedrock). Bai and Fernandez (2020) reported that for Maine, the USDA SSURGO soil database methodology defines soil as 200 cm deep, but the mean soil depth across all 1874 pedons in Maine was 138 cm.

While the terms forest floor and O horizon can have different meanings, here we take those terms to represent the same uppermost organic forest soil horizon. What is represented in scientific literature is often dependent on the specific methods used in the study. Most research to date focuses on carbon dynamics within the forest floor, where carbon often has a shorter residence time than at greater soil depths (Nave et al. 2019). However, meta-analyses investigating the forest floor, uppermost mineral soils, and deeper soil layers suggest that SOC responses to management practices often vary by soil depth, highlighting the importance of understanding carbon dynamics further below the soil surface (James & Harrison 2016; Kaarakka et al. 2021; Nave et al. 2010). For the purposes of this report, we distinguish between management effects in the forest floor or O horizon and deeper mineral soils whenever possible.

Natural and environmental factors including temperature, soil texture, tree species, and forest stand composition have significant influences on SOC dynamics within forests (Augusto et al. 2014; Devi 2021; Nave et al. 2021; Vesterdal et al. 2013). Lower air temperatures tend to promote higher stocks of SOC due in part to slower decomposition of organic matter, while soils with higher fractions of sand tend to have lower amounts of SOC (Devi 2021) reflecting lower storage capacity of those types of mineral soil materials. In a recent review on the influence of trees on SOC, Devi (2021) concluded that mixed species stands tend to have higher concentrations of SOC than monospecific stands, with the highest concentrations found in stands with mixed coniferous species. This finding could highlight the limitations of relying solely on a single species for forest management, and suggests that increased SOC storage may be a co-benefit of mixed stands in addition to benefits in biodiversity, economics, and overall forest health (Liu et al. 2018). In general, coniferous species accumulate greater SOC than deciduous species (Augusto et al. 2014; Vesterdal et al. 2013), due in part to the slower decomposition of conifer needles that can lead to organic matter buildup and thus greater SOC storage (Devi 2021). Research from Maine forests comparing SOC content and concentration in coniferous spruce-fir stands with primarily birch-beech-maple hardwood stands supports this finding (Fernandez 2008).

Keeping existing SOC stocks in the soil is a key goal of forest soil carbon management practices. In addition, forests often hold the greatest potential for SOC sequestration compared to croplands, wetlands, and other natural lands, with forest management pathways accounting for over 60% of the climate mitigation potential of cost-effective natural climate solutions globally (Griscom et al. 2017).

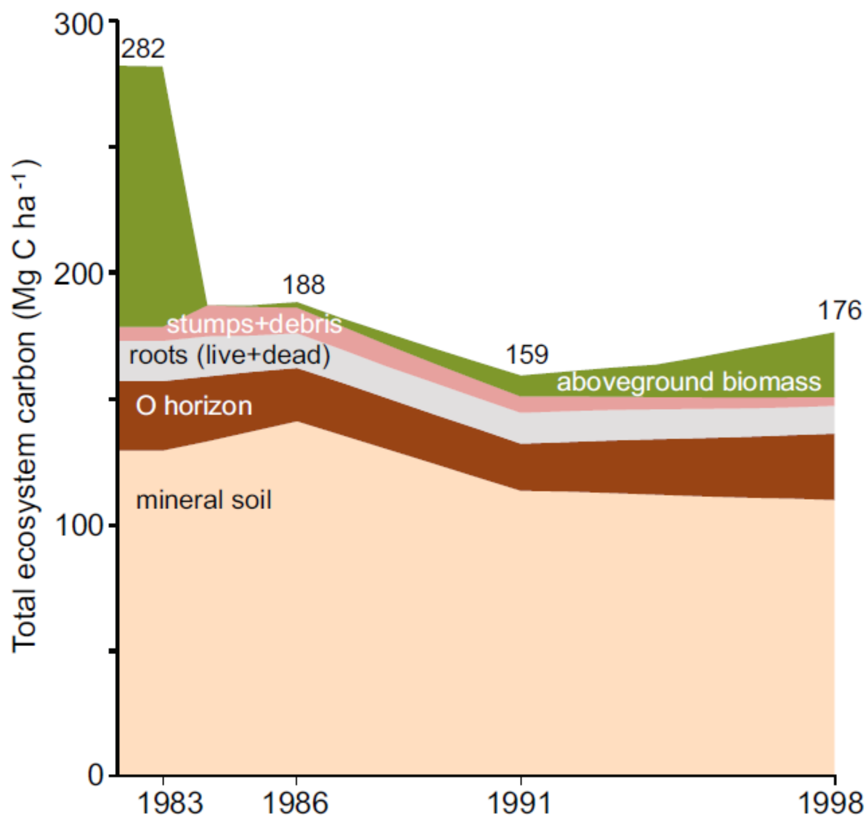

Figure 7. Total ecosystem carbon stocks at the Hubbard Brook Experimental Forest, Watershed 5, during the first 15 years following a whole-tree harvest. Total mineral soil thickness in this study averaged 53 cm to the top of the C horizon or bedrock, generally getting thinner with higher elevation. (From: Hamburg et al. 2019)

1.2.2 Management Practices to Increase Carbon Sequestration

Many forest management practices have the potential to impact SOC stocks and sequestration rates (**Figure 8**). Here, we will discuss practices that appear most often in the literature on forest SOC dynamics, including harvesting intensities (Covington 1981; Nave et al. 2019; Nave et al. 2021), land conversion to forests (Griscom et al. 2017; Nave et al. 2019), and avoiding forest conversion to other land uses (Catanzaro & D'Amato 2019; Griscom et al. 2017). Among these practices, there are often trade-offs; while avoiding harvesting timber allows greater stores of SOC to accumulate in the soil, active management can also help reduce the risk of losses in SOC storage due to disturbances including windstorms and wildfire (Bradford et al. 2013; D'Amato et al. 2011). Besides management factors, forest tree species composition, soil conditions, climate, and topography of a forest all influence SOC and contribute to variations in SOC content among stands (Devi 2021; Nave et al. 2019). Wildfires, prescribed fires, and other natural disturbances may also have ramifications for SOC dynamics (Nave et al. 2021; Pellegrini et al. 2017; 2020; Pellegrini, Caprio et al. 2021; Pellegrini, Harden et al. 2021; Wei et al. 2021).

Figure 8. Forest management practices reviewed by Mayer et al. (2020) that impact SOC stocks.

Research from Maine forests suggests that harvest intensity may be less influential to SOC than the timing of harvests, species composition, and overall forest productivity (Puhlick, Weiskittel et al. 2016). There were no significant differences between selection, shelterwood, and clearcut harvesting on SOC stocks in the mineral soil (Puhlick, Fernandez et al. 2016) or O horizon (Puhlick, Fraver et al. 2016) in mixed species stands of the Penobscot Experimental Forest (PEF) in central Maine after 60 years of various harvest management regimes. Clearcut harvesting did, however, significantly reduce total ecosystem carbon, which includes carbon found in aboveground tree biomass, more than shelterwood or selection harvesting (Puhlick, Weiskittel et al. 2016).

Harvesting in the PEF traditionally occurs during winter months, which results in low levels of physical disturbance to the forest floor and could have contributed to the lack of changes in O horizon SOC (Puhlick, Fraver et al. 2016). In addition, logging residues were not removed from harvest sites, allowing the remaining organic matter to be incorporated into the O horizon and contribute to SOC stocks (Puhlick, Fraver et al. 2016). In some cases, forest stands with the same harvest treatment still revealed significant differences in O horizon and total ecosystem carbon pools, suggesting that factors including harvest timing, species composition, and the amount of woody organic matter within the forest floor had a greater influence on SOC than the type of harvest (Puhlick, Fraver et al. 2016; Puhlick, Weiskittel et al. 2016).

Harvesting by clear cutting and thinning was found to reduce SOC by an average of 11.2% in a meta-analysis of harvest effects on forest SOC around the globe (James & Harrison 2016). This is slightly greater than the previous findings from Nave et al. (2010), which showed a ~8% decrease in forest soil carbon due to harvesting, largely due to the more recent study's inclusion of the mineral soil layer in their analysis (James & Harrison 2016). Soil depth was a critical consideration; while the largest percentage of SOC loss was in the O horizon (~30%), the harvest types and intensities did not show any significant differences in SOC loss except in the mineral soil horizons. In a meta-analysis of harvesting impacts in temperate forests, SOC losses were greater in the forest floors of hardwood forests (~36%) than in coniferous or mixed stands (~20%) (Nave et al. 2010).

Soil disturbance from logging equipment and site preparation, such as prescribed burning or tillage, is a major driver of SOC losses due to harvest (James & Harrison 2016; Kaarakka et al. 2021; Mayer et al. 2020; Thiffault et al. 2011). Practices that protect soil from compaction, such as timber mats, using skid trails, and limiting harvest to winter months could be useful in reducing SOC losses from harvest or thinning (Kaarakka et al. 2021). Identifying and targeting areas that are particularly prone to compaction, such as the soil alongside trails near landings in northern Maine hardwood forests (Puhlick et al. 2020), could further reduce losses of SOC.

A key consideration in implementing SOC-friendly practices is the length of time required for SOC stocks to recover after harvest. SOC decreased by 15% after a whole-tree harvest at the Hubbard Brook Experimental Forest, and had not recovered by year 15 following harvest (**Figure 7**), suggesting that forest regrowth may take longer than previously expected to offset SOC losses from whole-tree harvest (Hamburg et al. 2019). In a classic study of forest harvesting effects, 15 years after clear cutting, the amount of organic matter in the forest floor was still 50% less than before harvesting (Covington 1981). After year 15, the forest floor was restored to accumulating more organic matter than it lost (Covington 1981), but in many forests SOC pools may not recover from harvesting for several decades (James & Harrison 2016).

One challenge in determining the long-term effects of harvesting on SOC, however, is in differentiating between decreased forest floor SOC lost to the atmosphere and forest floor SOC that migrates downward to underlying mineral soils (Yanai et al. 2003). In north-central Maine, reductions in forest floor SOC 35 years after harvesting were offset by a net gain of SOC in the mineral soil over the same time period, which led to an overall non-significant effect of harvesting on total SOC stock (Smith, Briggs et al. 2022; Smith, Preece et al. 2022). The authors of the study suggest this lack of overall change could be due to downward migration of SOC from the forest floor to mineral soil over time, providing further support for the need to investigate SOC at a range of soil depths to fully determine management effects and the realized consequences to the atmosphere.

Post-harvest management practices also have impacts on forest SOC stocks. Residue removal generally decreases SOC content (James et al. 2021; Mayer et al. 2020). In a meta-analysis of the effects of forest harvest and biomass removal on SOC, whole-tree harvesting with residue removal lowered SOC levels by 24.9% compared to unharvested areas (James et al. 2021). Whole-tree harvest with forest floor removal also significantly lowered SOC relative to bole-only harvesting (James et al. 2021). The authors concluded that whole-tree harvesting with only some residue removal (less than 80%) could provide a sustainable balance between mitigating SOC losses and using residues for bioenergy production.

Prescribed burning after harvest and other prescribed fire practices also generally lead to losses in SOC. In meta-analyses on the effects of fire on SOC, broadcast burning led to significant SOC reductions in both the O horizon and mineral soil layers (James & Harrison 2016). Prescribed fire led to SOC losses, but these were much less severe than losses due to wildfire (Nave et al. 2019), suggesting that prescribed fire may mitigate SOC loss in fire-prone areas. In forested areas of the Western U.S., implementing thinning and prescribed fire practices in even 10% of fire-prone areas could prevent losses of up to 350 MmtCO_2e (CSP 2021). Overall, Nave et al. (2021) concluded that effects of fire varied with soil depth, where upper soil layers experienced significant declines in SOC, while deeper layers had the potential for SOC gains following fire disturbance (Nave et al. 2021). Due to this variation, there was no net effect of fire on SOC from the whole soil ecosystem, highlighting the necessity of examining SOC responses in a wide range of soil depths to fully understand the effects of fire and the realized impacts on carbon emissions to the atmosphere.

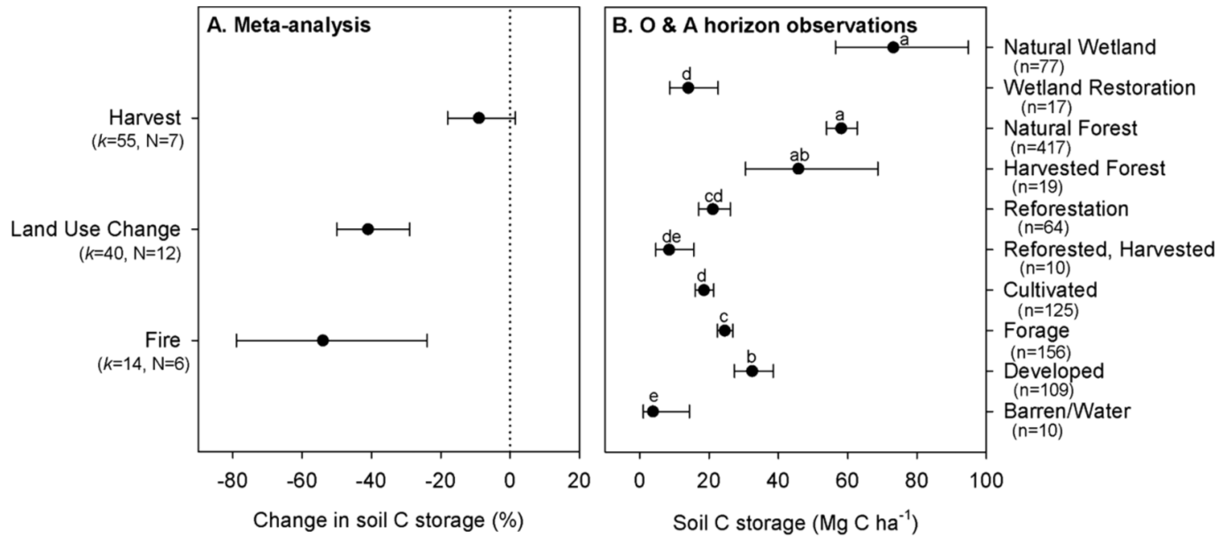

Figure 9. (A) Changes in the amount of SOC stored with different disturbances to a forest system, and (B) measurements of SOC stored in different land use types including several categories of wetland, forest, and agricultural land (From: Nave et al. 2019).

Reforestation - restoring historically forested areas - can also have varied effects on SOC, depending in large part on the previous type of land use. Reforestation of 10-30% of suitable private lands in the United States that historically supported tree cover (approximately 114 M acres) could sequester 150-550 MmtCO$_2$e between 2021 and 2030 (CSP 2021). In parts of the eastern U.S., reforestation led to gains in SOC compared to cultivated lands; however, SOC stocks still remained significantly lower in reforested areas than in natural forests (**Figure 9**; Nave et al. 2019). Riparian forests may provide a key opportunity for reforestation due to their favorable conditions for SOC storage and sequestration, including moist soils, sediment deposition, and complex vegetation growth (Sutfin et al. 2016). Model estimates from a global meta-analysis predicted that riparian forests would increase SOC by over 200% over 200 years compared to an unforested baseline (Dybala et al. 2018). However, another recent meta-analysis showed that reforestation only significantly increased SOC in mineral soils when barren minelands were converted to forest, with no significant effect on mineral soil carbon due to cropland conversion, highlighting once again the importance of considering soil depth (Nave et al. 2021).

Afforestation - planting trees in areas that are not forested, such as croplands - may increase, decrease, or have little effect on SOC stocks depending largely, again, on the former type of land use. Cropland conversion to forests often yields significant increases in SOC stocks, while afforestation of grasslands led to much lower increases in SOC or, in many cases, reduced SOC over the first 100 years (Mayer et al. 2020).

When considering overall forest management practice effects on SOC, the meta-analysis by Nave et al. (2019) ultimately concluded that management often has less of an influence than environmental and soil characteristics. Species composition and soil taxonomy (Devi 2021; James & Harrison 2016; Nave et al. 2010) and climatic factors including temperature and precipitation (Devi 2021) are key drivers of how SOC responds to forest management (Nave et al. 2021). Site-specific management that incorporates highly localized environmental and soil characteristic data will be critical to effectively improving SOC stocks on forested land (Nave et al. 2019).

Towards this end, Ontl et al. (2020) developed the *Forest Carbon Management Menu* to help forest landowners take action to reduce the risk of climate change impacts while achieving management goals. Communicating co-benefits of management strategies for increasing SOC, while identifying the long-term impacts of management practices and the vulnerability of specific locations to climate change, will be important to successfully managing forested land for carbon sequestration and storage (Ontl et al. 2020).

Improved forest management practices that aim to address multiple management objectives, such as maintaining or improving yields while reducing environmental impacts, also show potential for improving SOC sequestration (Kaarakka et al. 2021; Kauppi et al. 2022). While there is still a critical need for empirical data connecting the impacts of best management practices (BMPs) with SOC dynamics, guidelines found in technical reports for BMPs in Maine (Benjamin [Ed.] 2010) and the Northeast (FG-BWG 2010) provide useful information outside of peer-reviewed literature.

1.2.3 Directions for Future Research

Research to date shows that forest management practices can have the potential to improve SOC sequestration, but responses can vary greatly with soil depth, soil types, and other environmental factors. Invasive earthworms, as well as invasive plants and insects, for example, may play an increasingly important role in influencing SOC by altering the structure of forest soils (Bohlen et al. 2004; Lubbers et al. 2013), and have even been found to reduce forest SOC stocks in a recent study from northern Maine (Puhlick et al. 2021). Further research will be needed to build our understanding of how management and environmental factors, such as soil characteristics and the presence of invasive soil organisms, interact to influence SOC stocks.

Specific areas of needed research include:

- Developing methods to measure and track changes in SOC due to environmental processes and land management (Fernandez 2008), including the long-term impact of BMPs on forest SOC.
- Long-term studies of forest SOC dynamics under various management scenarios across a range of soil types and depths (Mayer et al. 2020).
- Further analysis of datasets across larger spatial scales needed to identify specific effects of tree species and sites on SOC (Devi 2021).
- Interactions between total ecosystem carbon, forest management, and climate across a wide range of forest types (Puhlick, Fraver et al 2016).
- Long-term studies to determine when, or if, SOC rebounds to pre-harvest levels, as well as the impacts of frequent partial cuttings on SOC (Hamburg et al. 2019).
- Impact of invasive plants and insects in forests on forest SOC.

1.3 Wetlands

The literature on management impacts to wetland SOC pools is scant in comparison to the bodies of work that exist related to agricultural and forest management. Much research has been done on SOC dynamics in wetlands (e.g., Kayranli et al. 2010; Krauss [Ed.] 2021; Nahlik & Fennessy 2016; Salimi et al. 2021; Yu et al. 2012), but less specifically on wetland management practices that influence SOC. This represents a key knowledge gap which will require considerable field and laboratory research by the scientific community. The following is a high-level summary of some key findings and considerations relevant to management practices impacting SOC pools in wetland systems.

1.3.1 Soil Carbon Dynamics in Wetland Systems

Maine has close to 5.4 million acres of freshwater and estuarine wetlands statewide (~25% of the state), more than the wetland area of the other New England states and New York, combined (Maine DEP 2003). Freshwater wetlands include forested swamps, floodplains, bogs, marshes, and vernal pools. Approximately 500,000 to 750,000 acres of Maine's wetland area are peatlands (MGS 2019), which globally store 15-30% of the world's SOC (Limpens et al. 2008), more than any other type of wetland. Maine also has approximately 22,000 acres of tidal marshes (Cameron & Slovinsky 2014), which have tremendous carbon burial capacity, up to 10-15 times more carbon buried per acre every year than an average acre of forest (McLeod et al. 2011). Maine's eelgrass meadows also have substantial carbon sequestration capabilities and should be considered part of the suite of coastal wetland contributions (Unsworth et al. 2022). Additionally, Maine's wetlands are generally in good to excellent condition, and results of the 2011 USEPA National Wetland Condition Assessment, a field-based effort to evaluate wetlands in the conterminous US (USEPA 2016), indicated Maine had better quality wetlands on average than other New England States. This includes many of Maine's floodplain forests and other riparian areas that not only have conditions favorable to carbon storage and sequestration, especially those floodplains which are wider with complex channel systems (Dybala et al. 2018), but also are recognized for significant contributions of other ecosystem services, biodiversity, and potential for climate resiliency and connectivity for species movement. The overall natural condition, together with the extensive acreage and diversity make wetlands in the State of Maine a highly valuable asset for biodiversity and natural climate solutions including carbon storage.

1.3.2 Management Practices to Increase Carbon Sequestration

Undisturbed wetlands act as large SOC sinks (**Figure 9**), and therefore are critical to keep intact to avoid releasing stored carbon (Limpert et al. 2020; Moomaw et al. 2018). Rehabilitating wetlands from previously degraded or disturbed sites, however, has been cited as being effective in increasing SOC sequestration (Limpert et al. 2020). For example, carbon emissions in a semi-arid Australian floodplain were reduced by 28-84% during and after a 'rewetting' event, where water was actively reintroduced to a degraded wetland (**Figure 10;** Limpert et al. 2020). This reduction was influenced both by changes in microbial decomposition rates and by higher rates of plant growth that increased carbon sequestration (Limpert et al. 2020). Soil organic carbon density has also been found to be greater in less disturbed wetlands compared to highly disturbed sites (Nahlik & Fennessy 2016), supporting the concept that avoiding wetland disturbances before complete rehabilitation is even necessary is an effective SOC management strategy (Krauss [Ed.] 2021). The conservation of wetlands and their buffers is a critical tool to protecting wetlands of all types, especially where run-off, development, and land clearing or conversion have the potential to directly impact wetlands and adjacent areas. Wetland conservation and restoration funding programs such as the *Maine Natural Resource Conservation Program* are therefore important to support for their role in compensating for wetland disturbance and maintaining "no-net-loss" of wetland area and function.

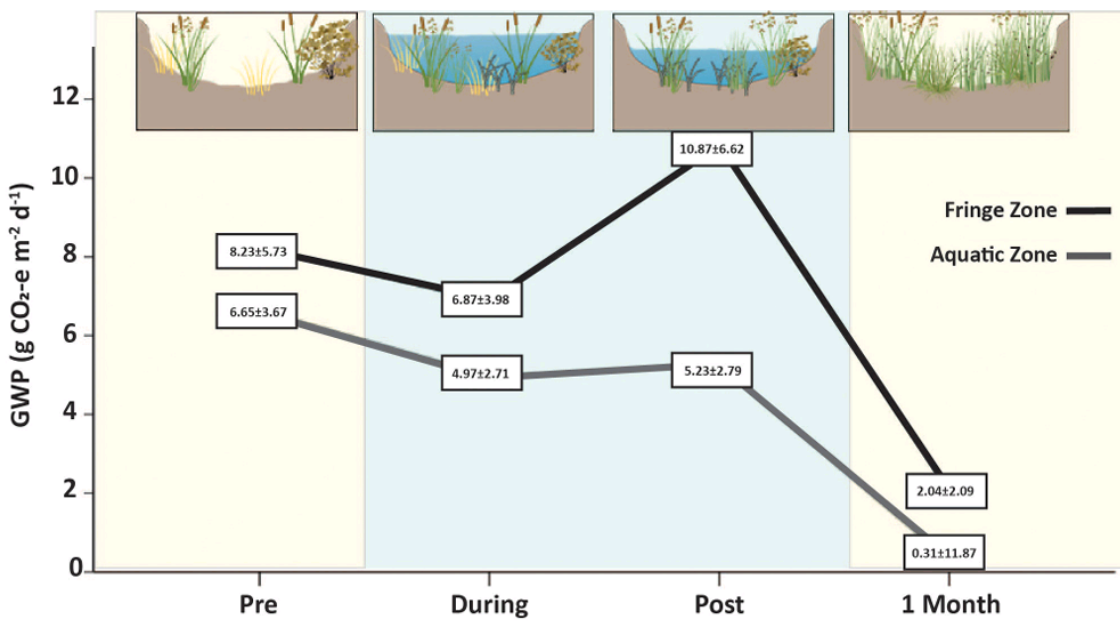

Figure 10. Total carbon emissions before, during, and after a prescribed watering event in areas submerged under water (the Aquatic Zone) and on the edges (the Fringe Zone) of a degraded wetland in Australia (From: Limpert et al. 2020).

Constructed wastewater wetlands and stormwater detention ponds are just beginning to be considered for their potential to have added benefits of sequestering and storing carbon, and in doing so act as net carbon sinks (Moore & Hunt 2011). Constructed wetlands can have large capacities for carbon accumulation, accelerated by sediment deposition that buries sequestered carbon in newly formed soil (McCarty et al. 2009). Estimates suggest that constructed or restored wetlands may sequester 2.7 to 4.5 tons C acre^{-1} year^{-1} (Anderson & Mitsch 2006). Methane emissions were also lower in constructed wetlands with alternating wet and dry cycles, compared to steady flow hydrologic conditions (Altor & Mitsch 2008).

Promoting the accumulation of blue carbon, the carbon stored in coastal wetlands including saltmarshes, eelgrass beds, and seaweeds, is a growing focus of conservation programs worldwide. Managed realignment - the process of breaching coastal defense structures to allow flooding of intertidal habitats - has shown promise in the United Kingdom, specifically, as the primary method of salt marsh restoration within the country (Austin et al. 2021). This practice leads to natural defenses against flooding and coastal erosion, rather than structural defenses. Practices for protecting and restoring salt marsh habitats that could also improve carbon storage include those that increase or stabilize sediment deposition, such as transplanting vegetation into unvegetated mudflats or using brushwood fences or coir logs to reduce erosion (Austin et al. 2021). Installing living shorelines (a type of green infrastructure) rather than hardened infrastructure to prevent shoreline erosion supports a suite of ecological services associated with coastal habitats, including allowing for natural sedimentation and vegetation growth needed for carbon burial (Woods Hole Group 2017). Eelgrass beds, which have both a significant ecological role in the marine environment and a role in mitigating both carbon and methane emissions, are also highly sensitive to stressors including boats, water quality, aquaculture, and development (Unsworth et al. 2022) and therefore are an important management, restoration, and protection target.

Wetland rehabilitation is particularly effective in tidal marshes that are crossed by roads with inadequately sized culverts, thus creating a barrier to full tidal flow. Tidal restrictions can create significant upstream impacts to tidal marshes including erosion, decreases in salinity or ponding of freshwater. Tidal restrictions may also result in aeration and resultant decomposition and subsidence of marsh peat, and eventually loss of the vegetated marsh system, all of which have cascading impacts on both buried carbon and carbon storage abilities (Roman et al. 1984). Restrictions may also prevent tidal marshes from migrating inland in response to sea level rise, representing a threat to the longevity of these coastal systems and the carbon and nature-based solutions they provide (**Table 1**). Significant tidal restrictions alter bacterial assemblages and can ultimately result in an upstream marsh that is a source of methane (Poffenbarger et al. 2011), a greenhouse gas ~30 times more potent than carbon dioxide.

Table 1: Potential effects of tidal restrictions on upstream wetlands and associated nature based resources and functions. (From: USEPA 2020).

Resource / Function Affected	Proximate Cause	Potential Upstream Effects
Vegetation	Reduced salinity	Invasion of salt intolerant non-native invasives like *Phragmites australis* that drastically alter vegetative community structure.
Water Quality	Reduced tidal flushing	Decrease ability of tidal wetlands to remove pollutants such as metals and excess nutrients; promote conditions that favor the accumulation of harmful bacteria.
Salt Marsh Specialist Bird Species	Vegetation change; loss of tidal wetlands	Loss of breeding habitat for species like the saltmarsh sparrow (*Ammodramus caudacutus*), that are highly dependent on intact salt marsh.
Fish and Shellfish	Reduced tidal inundation; increased water velocity	Limited habitat availability and restriction of movements between upstream habitats and the estuary.
Greenhouse Gas Emissions and Carbon Sequestration	Reduced tidal inundation, salinity	Reduced or negative organic carbon accumulation rates, greater methane emissions.
Resiliency to Storm and Flood Events	Loss of tidal wetlands	Loss of wave attenuating and shoreline stabilizing effects of coastal wetlands.
Sedimentation and Subsidence	Reduced tidal inundation	Reduced vertical sediment accretion rate and marsh elevations.

Climate mitigation benefits from wetland restoration, though found to be effective, may not be immediate. The type of wetland is also an important factor in determining if the ecosystem becomes a net source of carbon, or if it removes more carbon from the atmosphere than it emits. Nontidal managed wetlands, for example, were shown to bury carbon more effectively than restored tidal marshes, but also released greater proportions of methane (Arias-Ortiz et al. 2021). In this instance, the restored nontidal wetlands had an immediate overall warming effect due to methane emissions, while the tidal marshes had a cooling effect due to greater rates of carbon sequestration. While carbon sequestration in the nontidal wetlands would eventually increase and neutralize the warming effect, this process could take 2-8 decades (Arias-Ortiz et al. 2021). Kroeger et al. (2017) compared the cooling potential of tidal restoration projects to other carbon management practices, including creation of salt marsh or seagrass beds, and rewetting of freshwater peatlands from soils that had been disturbed and drained. Tidal restoration of impounded and freshened wetlands proved to be more efficient for climatic cooling than the other scenarios, reducing sustained methane emissions up to 98% from pre-restoration levels.

Technical reports on tidal wetlands in Maine provide useful information outside of the published literature that could also help inform conservation and policymaking efforts. In the Maine Climate Action Plan (MCC 2020), the protection and restoration of blue carbon ecosystems is recognized as an important strategy for promoting natural carbon sinks. A recent census suggests that about 90% of roads that cross tidal wetlands restrict tidal flow (Bartow-Gillies et al. 2020), representing a key opportunity for restoration efforts. Furthermore, modeled changes in greenhouse gas emissions associated with removal of these tidal restrictions predict a decrease in carbon emissions of 8.0 - 44.0 Gg CO_2e/year (MCC-CMWG 2020). Notably, these model calculations are based on emissions factors from the mid-Atlantic, and therefore provide only a preliminary and coarse estimate of the carbon benefits associated with salt marsh restoration. Further research in Maine’s tidal marshes is needed to develop estimates based on more local environmental conditions. Nonetheless, the restoration of tidal exchange to restricted marshes has been identified as a powerful tool in mitigating GHG emissions and climate change. The *Tidal Restriction Atlas* created by the Maine Coastal Program provides further insights into opportunities for tidal wetland rehabilitation and climate resilience for coastal communities in Maine. The application of tidal restoration practices such as those promoted by *CoastWise* (draft state report) will provide a consistent focus toward restoration that will benefit tidal marsh resiliency and function.

Recent studies investigating the impact of nutrient enrichment in coastal marshes have also shown effects that could have implications for wetland carbon storage, including reductions in belowground plant biomass (Alldred et al. 2017), and increases in microbial respiration that could potentially lead to greater carbon emissions over time (Geoghegan et al. 2018). Actions to protect tidal marshes from nutrient inputs include the reduction of fertilizer use, promotion of green infrastructure and strengthened stormwater management tools for healthier watersheds (Macreadie et al. 2017).

Although tidal marshes are known to be even more efficient at storing carbon than terrestrial systems, Maine currently has very little published data on carbon stocks in coastal wetlands, representing a gap in quality, quantity, and coverage of coastal carbon inventory (Holmquist et al. 2018). It is anticipated that this dataset will triple in the near future with researcher contribution of data results, and thus better understanding of stocks and dynamics to inform policies and actions within Maine.

1.3.3 Directions for Future Research

Research on the impact of management practices beyond limiting nutrient inputs or simply conserving natural and buffered wetland areas and marsh migration spaces for carbon storage represents a key knowledge gap at this time. Additional areas of needed research include:

- Long-term studies of carbon dynamics in wetlands after wetland rehabilitation efforts (Limpert et al. 2020), including barrier removal.
- Increase use of modeling to predict restorative effects of removing tidal restrictions to inform compensatory mitigation efforts (USEPA 2020).
- Additional installed living shoreline projects in particular within the intertidal zone, accompanied by monitoring of efficacy and performance over time.
- Investigating blue carbon as a co-benefit of tidal wetland restoration (Austin et al. 2021).
- Expanding research of soil organic carbon in eelgrass beds, highly disturbed eelgrass beds, recently unvegetated eelgrass beds, and eelgrass beds in areas of high nutrient inputs from stormwater runoff.
- Understanding how current methane emissions from freshwater wetlands compare with the potential carbon emissions that would occur if the wetland was converted or degraded (Nahlik & Fennessy 2016).
- Identifying the impacts of climate change on hydrology and carbon dynamics in peatlands (Limpens et al. 2008) and other freshwater wetlands (Kayranli et al. 2010).
- Transdisciplinary research that connects questions of local wetland conservation with global climate change (Moomaw et al. 2018).

2. Monitoring and Research Needs

Long-term, regional-scale SOC monitoring techniques and networks are needed in order to assess the status of SOC across natural and working lands and monitor changes that occur based on evolving management practices over time. Numerous techniques for measuring and modeling SOC are already established and are also an active area of research, but monitoring programs at the scale needed to inform science-based policy now and over time have not been actualized.

Methods for estimating SOC stocks that could be integrated into monitoring efforts include direct measurements from the field, remotely sensed data, and modeling based on empirical data or processes (Paustian, Collier et al. 2019).

Conventional *direct field measurements* of SOC stocks require collecting volumetric soil samples from plot sites, drying and processing them for laboratory analysis, and using instrumental methods to quantify the total amount of organic carbon in the soil (Bai & Fernandez 2020; Paustian, Collier et al. 2019; Smith et al. 2019). Due to the time and labor involved, however, direct field measurements through destructive soil sampling are cost-prohibitive to pursue routinely over large scales (Paustian, Collier et al. 2019; Smith et al. 2019).

Methods using *visible-near infrared (VNIR) spectroscopy* are emerging as an alternative means to detect SOC in field or laboratory settings (Gholizadeh et al. 2021; Hikouei et al. 2021; McBride 2021, Paustian, Collier et al. 2019; Smith et al. 2019). Spectroscopy is often faster and requires less labor than traditional lab soil testing methods (McBride 2021); however, many researchers argue that it is not yet reliable enough in detecting many soil chemical properties (including organic carbon) to completely replace conventional methods (McBride 2021; Paustian, Collier et al. 2019).

In recent years, *remote sensing* technology has been gaining capacity to detect surface-level SOC (Cao et al. 2019; Hikouei et al. 2021; Vohland et al. 2022; Wang et al. 2022). Integrating data from airborne and satellite remote sensing with machine learning models enabled the large-scale quantification of SOC in bare surface soils in one study (Wang et al. 2022). Using remotely sensed VNIR data to build machine learning models was also an effective method for mapping soil bulk density (which influences wetland hydrology and is used to calculate total carbon storage in soils) in salt marshes, and could therefore show promise for efficiently identifying suitable sites for wetland restoration (Hikouei et al. 2021). However, remote sensing is currently limited in quantifying SOC by green vegetation cover and plant residues on the soil surface (Wang et al. 2022).

Digital soil mapping (DSM) - the use of geospatial techniques that incorporate field and laboratory data, spatially explicit environmental data, and the quantitative relationships between them to generate soil maps at a given scale (McBratney et al. 2003) - is an additional emerging tool that could be useful in SOC monitoring efforts, given the importance of soil type and properties in SOC dynamics. The Cooperative Forestry Research Unit (CFRU) at the University of Maine recently began the work of using DSM to map soils on 1.5 million acres or more of forested land in central Maine (CFRU 2021). However, besides this initial research from the CFRU, Maine lacks a research program to develop and evaluate the potential of digital soil mapping to meet SOC policy goals on its natural and working lands. Expanding DSM efforts and developing cost-effective methods for mapping soils at relevant geospatial scales are required before DSM can help inform statewide policies and programs.

Additional barriers to frequent, cost-effective SOC quantification include large spatial variability (Cao et al. 2019), low capacity to detect small changes in SOC relative to ‘background’ SOC stock (Paustian, Collier et al. 2019), and the lack of standardization for direct measurement methods (Demenois et al. 2021). To address these issues, Paustian, Collier et al. (2019) outlined a framework for a potential global soil information system that incorporates integrated data-model frameworks, expands direct SOC measurement efforts, establishes improved monitoring networks, and utilizes remote sensing and crowd-sourcing to gather data on management practices across various land uses (**Figure 11**).

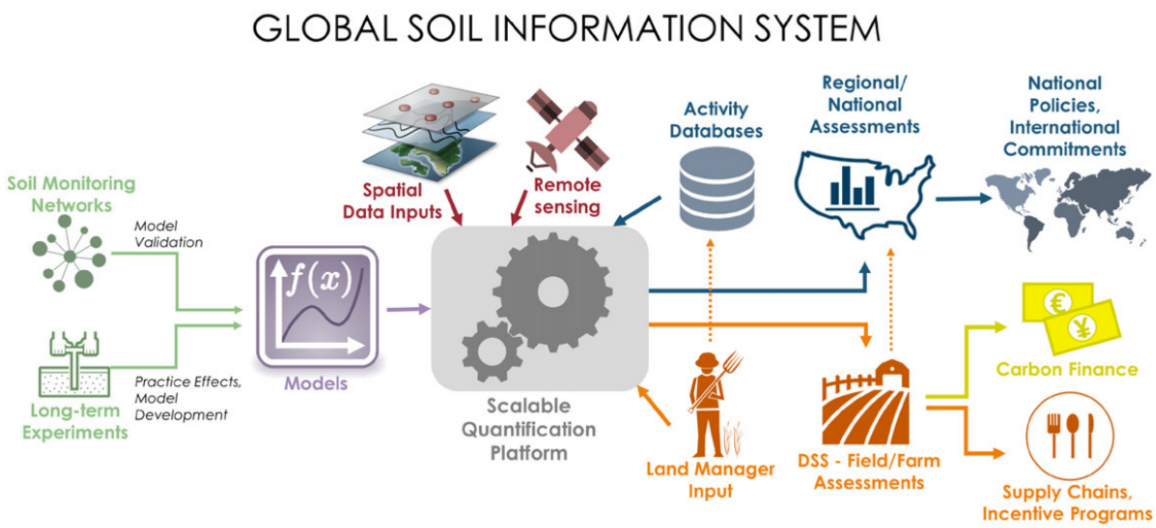

Figure 11. Overview of a proposed global soil information system based on long-term monitoring initiatives (From: Paustian, Collier et al. 2019).

Many researchers have also highlighted this urgent need for coordinated efforts to monitor SOC across larger scales (Harden et al. 2017, Smith et al. 2019) so that data on baseline conditions and changes in SOC over time with management interventions can be used to iteratively improve policymaking efforts. Understanding the factors that influence the abundance and dynamics of SOC over time will also be critical to predicting how SOC will respond to changes in the climate (Heckman et al. 2021).

Integrating multiple SOC estimation techniques and data sources - including direct field measurements, spectroscopic data, remote sensing, machine learning models, and user-reported management data - has been proposed as a foundation for potential monitoring efforts, in order to provide precise and accurate monitoring and to help overcome the limitations of each method individually (Paustian, Collier et al. 2019; Smith et al. 2019; **Figure 12**). Using multiple approaches would also enable SOC quantification across a range of spatial scales and levels of replication, which were found to be important factors in determining variation and predictors of SOC stocks (Nave et al. 2021). Soil depth is also consistently an important factor in estimating and predicting amounts of SOC (Heckman et al. 2021), and multiple integrated methods could potentially capture this variation more accurately. Incorporating soil depth repeatedly proves critical in determining the efficacy of practices intended to enhance SOC sequestration (e.g., Yang, Loecke et al. 2022).

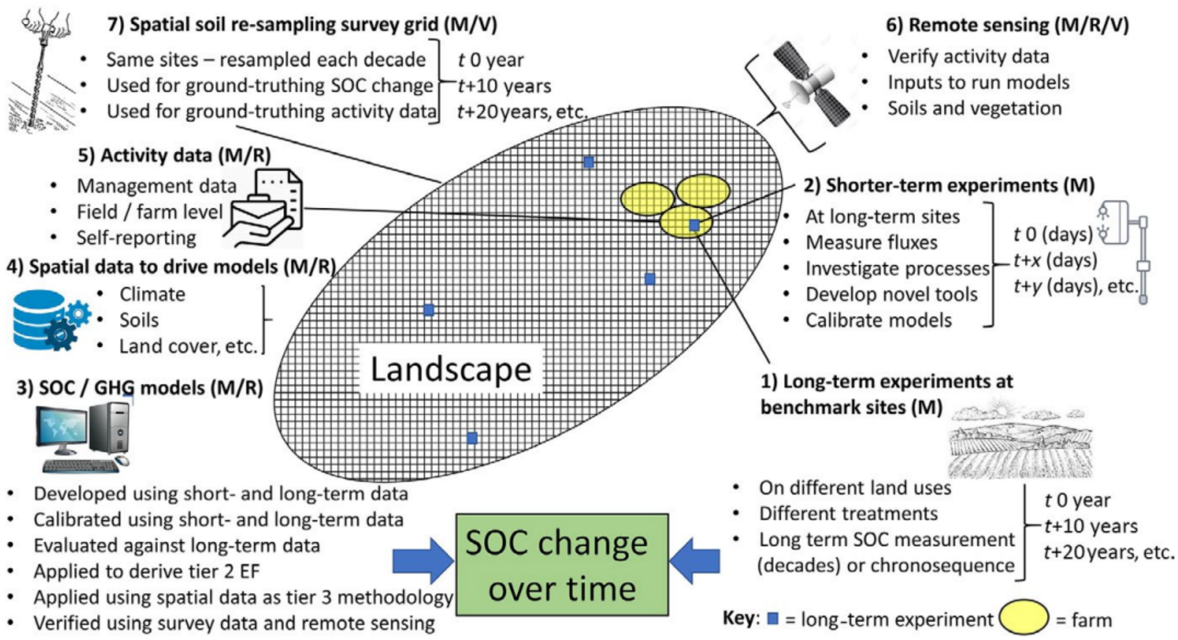

Figure 12. A conceptual framework illustrating the potential infrastructure and coordinated approach needed to develop a landscape-scale soil organic carbon (SOC) monitoring program (From: Smith et al. 2019).

Despite the need and the potential for useful frameworks highlighted in the literature, and despite the existence of soil carbon inventories, there are currently no soil carbon *monitoring* networks in the United States. Soil inventories that include data on SOC are used frequently in research, such as the USDA NRCS Soil Survey Geographic (SSURGO), the Forest Inventory Analysis (FIA), and the Rapid Carbon Assessment (RaCA) (Bai & Fernandez 2020), but there are no systematic efforts to monitor long-term changes in SOC that could be used for greenhouse gas accounting and to help inform policymaking (Smith et al. 2019). Given the importance of spatial scale (Cao et al. 2019; Nave et al. 2021), climate (Heckman et al. 2021), and land uses (Seaton et al. 2020) on SOC dynamics, developing a regionally focused SOC monitoring network represents a key opportunity for the Northeast.

Emerging networks such as the National Coordinated Soil Moisture Monitoring Network (Cosh et al. 2021) and the International Soil Carbon Network (Harden et al. 2017), which focuses on improving SOC measurement methods, and small-scale SOC monitoring experiments such as an ongoing study in Vermont's forests (Ross et al. 2021), could provide useful insights for future regional or national SOC monitoring efforts.

3. Existing Soil Carbon Policies and Programs in the United States

Existing programs across several states have been, or are being, developed to provide funding and technical support for natural and working land stakeholders to establish soil carbon–building practices. These programs can provide useful insights and frameworks for developing similar programs in Maine, and expanding existing programs. Out of the many state soil health programs in the United States, nine existing state programs and four recently passed state initiatives were selected for review in this report due to their specific inclusion of soil carbon storage or sequestration goals in their programming. Six non-governmental programs that either operate in the Northeast or have particularly innovative incentives for SOC storage (i.e. Land Core and the Carbon Cycle Institute) were also reviewed here.

The selected state programs range in focus from those solely addressing soil carbon to those that promote long standing soil conservation practices but include language identifying carbon sequestration as a co-benefit of such practices. **Table 2** contains a list of specific management practices funded to promote soil carbon sequestration and storage across the existing state programs reviewed, as well as practices that will be funded by recently passed legislation to create soil health programs in Colorado, Massachusetts, and Utah.

Table 2: Management practices funded by U.S. state programs that promote soil carbon storage and sequestration, based on the nine established and four emerging state programs reviewed in this report. If a program did not provide financial assistance for practices, or has not yet confirmed practices to be funded, they were not included in this table.

Management Practice	Number of Funded Programs	State(s) Funding Programs
Benefit-based practices[a]	5	CO, MA, MD, NM, VT
Conservation tillage	4	CA, NY, OK, UT
Cover cropping	3	CA, NY
Crop rotations	2	NY, UT
Composting	2	CA, UT
Manure management	1	NY
Water management	1	NY
Mulching	1	CA
Conservation plantings	1	CA
Conversion of marginal cropland to grassland	1	OK
Riparian buffers	1	OK

Management Practice	Number of Funded Programs	State(s) Funding Programs
Intercropping	1	UT
Planned grazing	1	UT
Revegetation	1	UT
Other soil amendments that add carbon or organic matter to the soil, including biochar, biosolids, and manure	1	UT
Other practices not specified	3	CA, OK, UT

[a]Benefit-based practices aim to achieve a certain soil health benefit or promote soil health principles specified by the funding state program, but are not limited to specific practices.

In general, states that have enacted the most ambitious and well-documented programs have chosen to allocate considerable resources to support practice implementation by land managers. Three of the existing state programs reviewed provided data on emissions reductions attributable to their programs; **Table 3** summarizes these outcomes, alongside data on funding allocated to land managers through these programs. In Maine, research is emerging that will begin to provide insights on healthy soils practices through demonstration and research, such as the *Maine Soil Health Network* developed by the Maine Farmland Trust and Wolfe's Neck Center.

Table 3: Summary of project funding and emissions reduction data from programs reviewed in this report that published their outcomes.

Program	Funding Provided	Outcomes
New York Climate Resilient Farming Program	$12 million to 200 farms since 2015	Estimated CO_2e emission reductions of 320,000 metric tons per year.
California Healthy Soils Incentives Program	Over $30 million to 604 projects between 2017-20	Estimated total CO_2e emissions reductions of 109,089 metric tons.
California Healthy Soils Demonstration Projects	$10 million to 71 projects between 2017-20	Estimated total CO_2e emissions reductions of 3,900 metric tons

The following sections provide brief synopses of specific programs from which useful insights may be drawn. These are organized into three major categories: established state programs, recently passed legislation, and non-governmental programs.

3.1 Established State Programs

Ongoing or completed programs from nine states were reviewed as part of this report. Summary descriptions of programs are highlighted in **Table 4**, including key attributes such as affiliated organizations, practices included, outcomes, and funding sources. **Tables 4** and **5** are dominated by examples focused on agriculture, where soil carbon specifically is identified as a goal. Far fewer examples exist for similar policies focused on soil carbon in forests and wetlands, where overall ecosystem carbon and other ecosystem services (e.g., biodiversity) are the primary goals. We have not attempted to inventory all policies that might impact soil carbon but do not explicitly refer to that desired outcome.

Table 4: Established state programs providing funding or technical support for management practices intended to store and sequester soil carbon on natural and working lands.

Program	Year Started	Affiliated Organizations	Goals	Program Description	Outcomes to Date	Funding Source(s)
Maine Healthy Soils Program	2021	Maine Department of Conservation, Forestry and Agriculture	Promote and expand the use of healthy soils best practices among farmers and farmland owners.	This newly established program (LD 437) will provide a one-stop-shop for farmers seeking information about how to keep their soils healthy. This information could include: healthy soils land management practices; technical assistance services offered by agriculture support providers to help farmers use these practices; connections to other farmers already using these practices successfully; funding opportunities to support the use of these practices; and more.	Program in its first year of planning.	Legislative appropriate to support the initial establishment of the program to date.
New York Climate Resilient Farming (CRF) Grant Program	2015	New York State Department of Agriculture and Markets; New York State Soil and Water Conservation Committee	Reduce the impact of agriculture on climate change and increase the resiliency of New York State farms in the face of a changing climate.	Provides grants through Soil and Water Conservation Districts for farmers to reduce greenhouse gas emissions by adopting practices related to: 1) manure management; 2) water management; and 3) soil health. Greenhouse gas emission reductions from projects are estimated using COMET Planner, an emissions modeling and planning tool developed by Colorado State University and the USDA-NRCS. Practices eligible for funding include: manure cover and flare systems to reduce methane emissions; water management practices that provide resilience to flood events and drought; soil health practices including basic and multispecies cover crops, conservation crop rotation, and conservation tillage.	Since 2015, CRF has awarded \$12 million to 200 farms, with \$8 million available to be awarded in 2022. Funded on-farm projects, including 26,000 acres of planted cover crops, are estimated to reduce CO_2e emissions by 320,000 metric tons/yr.	New York State Environmental Protection Fund.

Program	Year Started	Affiliated Organizations	Goals	Program Description	Outcomes to Date	Funding Source(s)
New York Soil Health Initiative	2017	New York State Department of Agriculture and Markets; Cornell College of Agriculture and Life Sciences; USDA Natural Resource Conservation Service	Build a network of agricultural stakeholders that promotes sharing information and facilitating farmer adoption of soil health practices by identifying barriers and opportunities.	Develops soil health publications and outreach programs for farmers and agriculture professionals, with a focus on improving management practices, climate resilience and water quality, perennial and urban agriculture, and soil health assessments.	Since 2017, \$1.2 million in funding has gone towards the New York Soil Health Initiative. Outreach programs have reached over 7,200 stakeholders. Resource outcomes include the New York Soil Health Roadmap and other publications, including a technical report on the Characterization of Soil Health in New York State.	New York State Environmental Protection Fund.
California Healthy Soils Program (HSP)	2017	California Department of Food and Agriculture	Promote the development of healthy soils on farms and ranches in California.	Supports farmers in building soil health through the HSP Incentives Program and HSP Demonstration Projects. The Incentives Program provides financial assistance to farmers for implementing practices that will improve soil health, sequester carbon, and reduce emissions. The Demonstration Projects program funds on-farm data collection and demonstrations of management practices that reduce emissions and improve soil health. Practices eligible for funding include but are not limited to: cover cropping, no-till, reduced-till, mulching, compost application, and conservation plantings.	The HSP Incentives Program funded 604 projects between 2017-20, with practices implemented across 51,300 acres. Estimated greenhouse gas reductions were 109,089 metric tons CO_2e. In 2020, the program awarded over \$21 million to applicants. The HSP Demonstration Projects have funded 71 projects between 2017-20 that reached over 1,200 farmers and ranchers. Demonstration practices have been implemented across 3,036 acres, leading to estimated greenhouse gas reductions of 3,900 metric tons CO_2e. In 2020, the program awarded \$2.9 million across all projects.	State cap and trade proceeds (\$40.5 million from 2016-19) and the California Drought, Water, Parks, Climate, Coastal Protection and Outdoor Access for All Act of 2018 (\$10 million).

Program	Year Started	Affiliated Organizations	Goals	Program Description	Outcomes to Date	Funding Source(s)
Vermont Environmental Stewardship Program (VESP)	2020	Vermont Agency of Agriculture, Food and Markets; Vermont Association of Conservation Districts; Vermont Department of Environmental Conservation; University of Vermont Extension; USDA NRCS	Promote water quality improvements through voluntary practice adoption, and provide social recognition for farmers who strive for a high level of land stewardship.	A pilot voluntary certification program for farmers who meet specific environmental standards in soil management, water quality, air quality, and pesticide management. Farmers meeting these standards receive a five-year certification as a Certified Vermont Environmental Steward and are provided with technical and financial support for implementing or maintaining practices to support nutrient management, sediment and erosion control, soil health, greenhouse gas emissions, and carbon sequestration.	As of 2020, 8 farms were enrolled including 6 dairy farms, 1 beef farm, and 1 diversified farm.	The General Fund and the Clean Water Fund.
Connecticut Soil Health Initiative	2021	Connecticut Department of Energy and Environmental Protection; Connecticut Resource Conservation and Development; Connecticut Council on Soil and Water Conservation; USDA NRCS	Encourage healthy soils.	Partners with USDA NRCS to provide interactive demonstrations and other outreach events for farmers on terminating cover crops, simulating rainfall on healthy vs. poor soils, and understanding soil properties by investigating soil pits. Advises the Commissioner of the Department of Energy and Environmental Protection on soil health matters and implementation of related programs.	Has developed workshops, field demonstrations, webinars, educational events, and pilot programs promoting soil health.	Previously existing funding sources through Soil and Water Conservation Districts.
Maryland Healthy Soils Program	2019	Maryland Department of Agriculture	Improve the health, yield and profitability of soils; increase biological activity and carbon sequestration in agricultural soils; and to promote education and adoption of healthy soil practices.	Provides technical and financial assistance to farmers through their Farming for Healthy Soil grants, which pay farmers $10 to $55 per acre for implementing conservation tillage, multi-species or extended season cover crops, prescribed grazing, or precision nutrient management practices.	In 2019, creation of a Soil Health Advisory Committee consisting of 32 stakeholder members to guide program development.	Information not provided.

Program	Year Started	Affiliated Organizations	Goals	Program Description	Outcomes to Date	Funding Source(s)
Oklahoma Carbon Program (OCP)	2010	Oklahoma Conservation Commission; Oklahoma Forestry Services; Oklahoma State University; USDA NRCS; U.S. Environmental Protection Agency	To encourage voluntary adoption of carbon sequestration or greenhouse gas reduction practices in order to protect water quality, prevent soil erosion, and improve air quality.	A carbon sequestration certification program that provides state-backed, fee-based verification of carbon offsets for aggregators who have carbon contracts with agricultural or forestry stakeholders. Practices eligible for funding include but are not limited to no-till, conversion of marginal cropland to grassland, and riparian buffers.	Information not provided.	Oklahoma Western Farmers Electric Cooperative; NRCS 2010 Conservation Innovation Grant; EPA 319 Nonpoint Source Program.
Healthy Soils Hawaii	2019	Hawaii Office of Planning; Hawaii Agriculture Research Center	Identify best management practices for soil carbon sequestration, soil health, and greenhouse gas emission reductions.	A one-year pilot program established through the Hawaii State Greenhouse Gas Sequestration Task Force.	Provided technical support for 10 farmers and ranchers to implement potential best management practices on their land, then used soil health data collected from the experimental sites and interviews with growers to make BMP recommendations for the state.	The task force still exists, but was defunded in the fiscal year 2019-20.
New Mexico Healthy Soils Program	2019	New Mexico Department of Agriculture	Promote land management that increases soil organic matter, aggregate stability, microbiology and water retention in order to improve soil health, yields and profitability.	Provides financial, technical, and educational resources to land managers. Funding applicants must identify soil-specific concerns (e.g. compaction, erosion, etc.) on the project site, and develop a conservation plan to address those concerns. Funded projects must implement one or more of the following principles: 1) keeping soil covered; 2) minimizing soil disturbance on cropland and minimizing external inputs; 3) maximizing biodiversity; 4) maintaining a living root; and 5) integrating animals into land management.	Information not provided.	The General Fund and the USDA NRCS

3.2 Recently Passed State Legislation and Initiatives

The states of Massachusetts, Utah, and Colorado have recently passed legislation that informs the development of statewide Soil Health Programs and related work in their jurisdictions, with stated goals of supporting soil carbon sequestration and storage. In addition, the governor of Oregon recently signed an Executive Order that calls for a proposal of carbon sequestration and storage goals for the state's natural and working lands. These acts are briefly summarized below.

In January 2021 Massachusetts signed into law "An Act to Promote Healthy Soils and Agricultural Innovation within The Commonwealth." This legislation directs their Commission for Conservation of Soil, Water and Related Resources (CCSWRR) to create and fund a Massachusetts Healthy Soils Program, which will aim to promote the implementation of healthy soil practices on private and public land by providing financial, technical, and educational assistance to land managers and landowners. The policy states that practices eligible for funding must "provide 1 or more of the following benefits: improve food production; encourage the health, growth and biological diversity of plants and forests; increase water infiltration reducing stormwater runoff; provide drought and crop resilience, enhance water quality; and reduce the use of fertilizers and herbicides; and provide greenhouse gas benefits."

In March 2021, Utah added Soil Health Amendments to the Conservation Commission Act, intended to promote the adoption of soil health practices. The legislation establishes a Utah Soil Health Program, which will provide resources for producers to implement soil health practices through grants, technical assistance, outreach efforts, and educational materials. Supported practices include but are not limited to no-till, conservation tillage, crop rotations, intercropping, cover cropping, planned grazing, revegetation, or application of soil amendments that add carbon or organic matter, including biosolids, manure, compost or biochar. Funding will be allocated from existing sources through the Utah Conservation Commission. Additionally, the bill calls for establishment of a state soil health monitoring platform to document the condition of agricultural soils, implementation of soil health practices, or environmental and economic impacts such as the carbon storage capacity of soils.

In June 2021, Colorado passed a bill "Concerning the Creation of a Voluntary Soil Health Program" that directs the CO Department of Agriculture (CDA) to create a Soil Health Program. This will include funding for Conservation Districts to provide technical assistance, incentive payments to producers, free soil health testing, educational resources, and soil health research. Funded projects must implement one or more of the following principles: 1) keeping soil covered; 2) minimizing soil disturbance on cropland and minimizing external inputs; 3) maximizing biodiversity; 4) maintaining a living root; and 5) integrating animals into land management. In addition, the CDA is tasked with developing a soil health monitoring and inventory system; and tasked with introducing the Saving Tomorrow's Agricultural Resources (STAR) program to Colorado, which is a free and voluntary rating system in which farmers receive one to five "stars" based on their use of practices to reduce nutrient and soil loss. Funding will be allocated through the General Fund, state stimulus funds, and an EPA Section 319 Nonpoint Source Pollution grant.

In March 2020, the governor of Oregon signed an Executive Order directing the Oregon Global Warming Commission (OGWC) to submit a proposal outlining state goals for carbon sequestration and storage on Oregon's natural and working lands, including agricultural lands, forests, and wetlands. The OGWC submitted their *Natural and Working Lands Proposal* in 2021, which calls for storing or sequestering an additional 5 million metric tons of CO_2e by 2030, and an additional 9.5 metric tons of CO_2e by 2050. Proposed strategies to increase sequestration in the state's natural and working lands include: "1) Leverage federal lands and investments in climate-smart natural and working lands practices; 2) investigate options and create a sustained source of state funding to increase sequestration in natural and working lands; 3) fund and direct agencies to take actions to advance natural and working lands strategies; and 4) invest in improvements to Oregon's natural and working lands inventory". Specific recommendations include establishing an agricultural program to incentivize adoption of climate-smart practices, developing a strategic plan for expanding reforestation in the state while incentivizing climate-smart forestry, and conserving or restoring tidal wetlands.

3.3 Non-Governmental Programs

Several non-governmental programs relevant to carbon storage and sequestration on natural and working lands were reviewed, and considered worthy of highlighting as additional examples to aid in the development of state programs that engage stakeholders and incentivize practice adoption. Summary descriptions of some example non-governmental programs, highlighting key attributes, are included in **Table 5**.

Table 5: Non-governmental programs providing funding or technical support for management practices intended to store and sequester soil carbon on natural and working lands.

Program	State / Region	Year Started	Affiliated Organizations	Goals	Program Description	Funding Source(s)
Climate Adaptation Fellowship	Northeast US	2020	University of Vermont Extension; USDA Northeast Climate Hub; USDA Northern Forests Climate Hub; University of Maine; Rutgers University; USDA Natural Resource Conservation Service; Forest Stewards Guild; Manomet	Promote climate adaptation among farmers and foresters through peer-to-peer learning with support from advisors.	Farmers, foresters, and service providers may apply to the one-year program to become Fellows. Once accepted, farmer and forester participants work with service providers to create individualized climate adaptation plans for their land and grow their understanding of climate change impacts and how to access and utilize localized climate data. During the year, Fellows attend two workshops that provide climate science education tailored to their area of management and facilitate networking among participants.	USDA National Institute of Food and Agriculture; USDA Joint Venture Agreement; Rutgers Climate Institute; University of Vermont Extension
Soil Technical Assistance - Soil Carbon Analysis	MA	Mid-2010's	Northeast Organic Farming Association - Massachusetts (NOFA-MASS)	Expand the production and availability of nutritious food from living soil for the health of individuals, communities and the planet.	Provides farmers with technical assistance to run a series of soil tests that provide data on the level of biodiversity and biological activity in the soil, which is used as an indicator of soil carbon storage levels. Based on test results, NOFA advisors provide farmers with an analysis of the health and carbon content of their soils, and management recommendations. Tests may be repeated annually to enable farmers to identify longer-term impacts of management decisions on soil carbon.	Information not provided.

Program	State / Region	Year Started	Affiliated Organizations	Goals	Program Description	Funding Source(s)
Million Acre Challenge (MAC)	MD	2020	Future Harvest: Chesapeake Alliance for Sustainable Agriculture; Fair Farms Maryland; Hatcher; Institute for Local Self-Reliance; Chesapeake Bay Foundation; Institute for Energy and Environmental Research	Help Maryland farmers build soil health, increase farm profitability, and improve water quality while making farms resilient and active in the face of climate change; one million acres of healthy soils in Maryland by 2030.	Focuses on building connections between farmers and facilitating peer-to-peer learning about soil health, while providing information and resources through the Pasa Sustainable Agriculture Soil Health Benchmark Study, educational opportunities, and regional Soil Health Hubs. To participate in the MAC, farmers fill out a self-assessment survey and are provided with tools and resources to track their soil health progress. The program also engages agricultural stakeholders and consumers in promoting and creating policies that incentivize soil health practices. In 2020, the MAC engaged 30 Maryland farmers participating in the Soil Health Benchmark Study, managing 4,000 acres. Over 150 farmers were engaged through soil health outreach and farmer-to-farmer learning events.	USDA NRCS Regional Conservation Partnership Program; direct donations.
Healthy Soils Grants	VT	2021	Vermont Land Trust; University of Vermont; Bio-Logical Capital.	Support Vermont farmers in combating climate change by evaluating the ecological, economic, and social impacts of adopting soil health practices.	Aims to provide funding for 16-20 Vermont farms over five years (2021-2025) to implement soil health management practices integrated with grass-fed livestock. Participating farmers will receive payments for each practice on a per-acre basis, and technical support and mentorship from agricultural service providers. Farmers will also have access to comprehensive field data collected from each farm to identify the ecological, economic, and social impacts of the practices. All four of the following practices must be incorporated: no-till cover crops, finished compost application, subsoil keyline plowing, and Management Intensive Rotational Grazing (MIRG).	USDA NRCS Conservation Innovation Grant

Program	State / Region	Year Started	Affiliated Organizations	Goals	Program Description	Funding Source(s)
Carbon Farm Planning (CFP) and Carbon Farming Network (CFN)	CA	2013 (CFP) and 2016 (CFN)	Carbon Cycle Institute; California Resource Conservation Districts	Stop and reverse global climate change by advancing natural, science-verified solutions that reduce atmospheric carbon while promoting environmental stewardship, social equity, and economic sustainability.	The CFP program connects farmers and ranchers with a team of advisors to identify pathways for greenhouse gas reductions and increasing carbon sequestration on their land. Impacts are estimated using the COMET Planner modeling tools. Partnering with Resource Conservation Districts, the Carbon Cycle Institute also developed the CFN, comprised of over 100 Resource Conservation Districts professionals now trained as carbon farm planners. CCI helped establish carbon farming programs at 32 Resource Conservation Districts across California. The CFP and CFN programs have resulted in completion of 137 carbon farm plans, encompassing over 70,000 acres of farm and ranch land. If fully implemented, this has the potential to sequester 1.7 million metric tons of carbon after 20 years.	Information not provided.
Outcomes-Integrated Land Lease Program	US National	2021	Land Core	Contribute towards reversing soil erosion, quantifying potential carbon capture, and generating consistent outcomes data on the ecological and risk-mitigation impacts from participating farms.	A pilot program in which landowners and tenants negotiate long-term leases with specified benchmarks for key soil health indicators that must be met over time. Tenants will be connected to a network of funders who will provide access to low / no interest loans and grants for regenerative agriculture projects. Required soil health outcomes will be based on the NRCS "Science of Soil Health" testing protocols, with indicators including increases in soil organic matter, water infiltration rates, soil aggregates, and water quality.	Information not provided.
Forest Soil Carbon Initiative	Northern US	2018	American Forests; Northern Institute of Applied Climate Science; Sustainable Forestry Initiative; University of Michigan; Maryland Dept. of Natural Resources Forest Service	Gather data on the dynamics of soil carbon in forests and how they may be impacted by certain management decisions and practices.	In 2018, American Forests partnered with the Maryland Department of Natural Resources to analyze the state of soil carbon in its forest's soils and identify areas where soil carbon may be particularly vulnerable to loss. American Forests is currently working on similar research with state agencies in Oregon, Washington, Minnesota, Michigan, Wisconsin, and North Carolina.	Sustainable Forestry Initiative Conservation Partnerships Grant Program

Blue Carbon Network	US National	2022	The Pew Charitable Trusts	Provide local, state, and national stakeholders with resources and opportunities to connect and share information regarding blue carbon policy and best management practices.	The Blue Carbon Network from Pew is in its beginning stages, and potential members include state employees, researchers, academics, NGO professionals, and other stakeholders working on blue carbon projects or policies. The network will provide opportunities for information-sharing and discussion around numerous topics, including developing greenhouse gas inventories for state coastal wetlands, dealing with the effects of sea level rise on sequestered and stored carbon, setting coastal habitat conservation and restoration targets, and navigating funding and monitoring challenges and opportunities for blue carbon projects.	Information not provided.

Conclusions

The management practices employed on natural and working lands by farmers, landowners, and land managers have substantial ramifications for sequestration of SOC. Policies and incentives that conserve carbon stocks already present in soils and restore or add to existing stocks may aid the State of Maine in achieving its climate change mitigation goals. This technical report to the Maine Department of Agriculture, Conservation and Forestry and the Department of Inland Fisheries and Wildlife is intended to support these Departments in developing their recommendations to the Joint Standing Committee of the Maine Legislature on Agriculture, Conservation and Forestry. This technical report shares findings and recommendations regarding programs and policies to aid in climate mitigation and resilience by promoting and incentivizing practices to increase sequestration of SOC on natural and working lands in Maine as put forth in LD 937.

The literature review of management practices that enhance carbon in agricultural, forest, and wetland soils contained in this report indicates that a deep body of research exists with regard to this topic for agriculture, and substantial information with utility to inform policy exists for forestry, but comparably little management research has been conducted in wetland systems. It is also important to identify our state-of-knowledge from the body of scientific literature overall, as well as the evidence for how this science can be applied to Maine natural and working lands, our economy, and the communities that depend on them. Additional information to inform Maine policy resides in various programs, the "gray" literature, and stakeholder experience. Conservation practices that prevent ecosystem degradation and disturbance, especially in forests and wetlands, show some of the greatest potential for maintaining or improving stores of SOC in Maine. Providing incentives for land managers to adopt best management practices, while conserving ecosystems that have a high capacity for SOC storage and sequestration, should be priorities for policies that aim to mitigate climate change on Maine's natural and working lands. The value assessment of investments in natural and working lands should consider more than just carbon, but be evaluated in the full context of improvements of other ecosystem services as well.

A comprehensive framework or functioning network for statewide soil carbon monitoring to inform policy and management at all relevant scales and define science-based best practices does not yet exist. However, well-developed theoretical frameworks and practices can serve as templates for creating the infrastructure to conduct such ongoing monitoring, should funding and support be allocated to this important work.

Several other states have or are in the process of enacting policies to support soil carbon storage, including nearby Vermont and Massachusetts. Some of the most developed and effective policies reviewed to date have been developed in California, New York, Maryland, and New Mexico, while other New England states are in various stages of developing healthy soil policies and programs. These policies, which mainly focus on agricultural management, aim to provide support to farmers and land managers in a variety of ways, including financial, technical, and educational assistance. One key take-away from this overview of programs is that well-funded initiatives can lead to real-world results in reducing CO_2 emissions. New York and California, the two states that published emission reductions data from their soil health initiatives, provided on average $5 million per year to the farmers and land managers who participated in their programs. Both states estimated notable reductions in CO_2 emissions from agriculture as a result (see **Table 2**). In addition, multiple programs have prioritized sharing soil health and carbon data collected from project sites with the farmers or landowners who manage those sites in order to support data-driven management decisions. Well-funded incentive programs that also provide practical data and information to land managers meet multiple stakeholder resource needs that can help improve the implementation of practices to increase soil carbon storage and sequestration on natural and working lands.

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