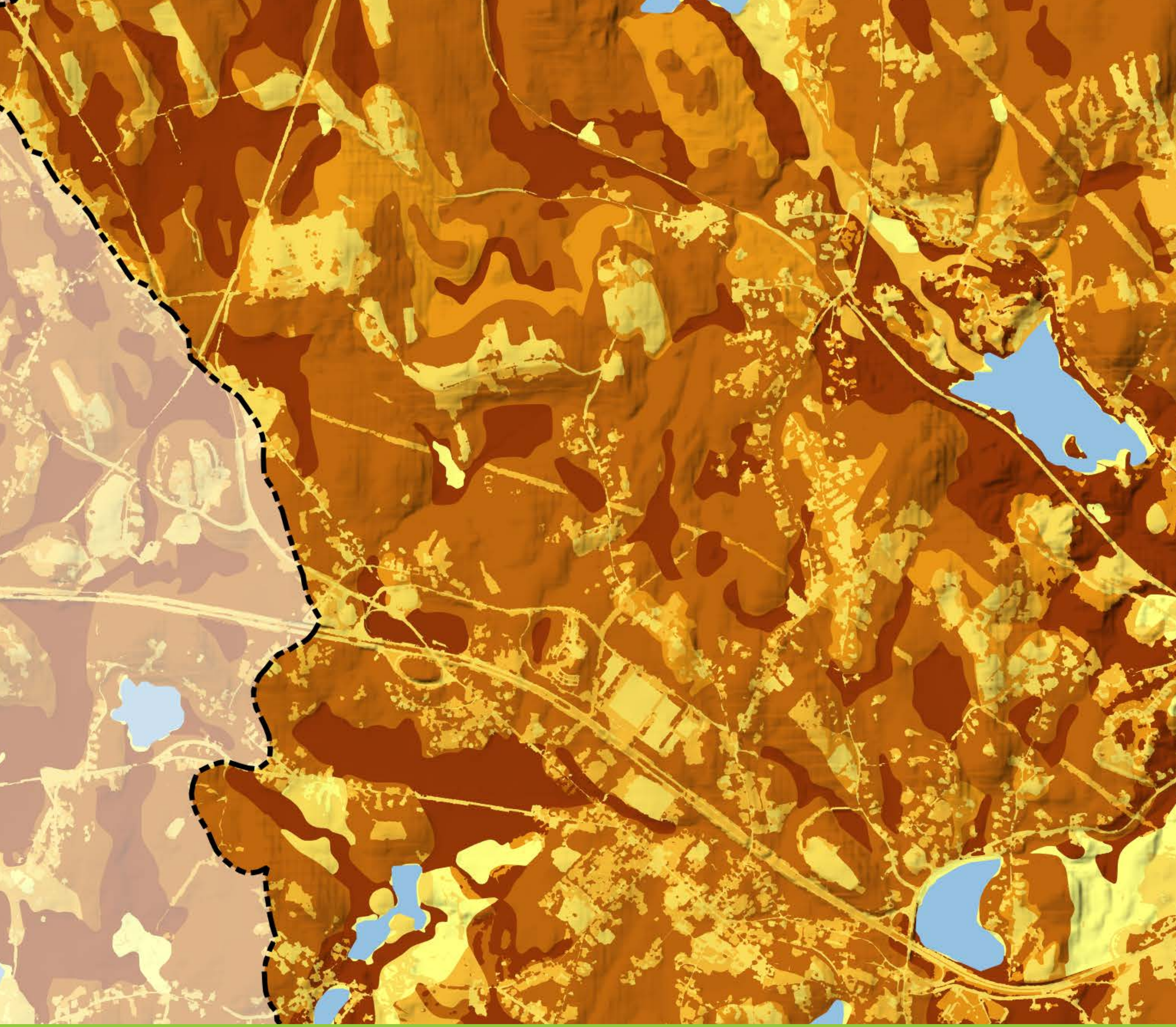

Soil Organic Carbon Mapping Project

Proposal for a Healthy Soils Action Plan Challenge Grant

Submitted to the Massachusetts Executive Office of Energy and Environmental Affairs

Prepared by Regenerative Design Group

January 2024

Challenge Grants Implementing the Commonwealth's Healthy Soils Action Plan
Commbuys Bid #BD-24-1042-ENV-ENV01-96064
RFR ID: ENV 24 DCS 08

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Revised: February 1, 2024

Contents

Cover Letter

Tom Anderson
100 Cambridge Street
9th Floor
Boston, MA 02114

Dear Mr. Anderson,

As the primary consultants on the 2023 Healthy Soils Action Plan, it has been extremely encouraging to see the progress the EOEEA has made over the last year toward implementing the recommendations, including the RFR for the Healthy Soils Challenge Grant Initiative released in December. We are pleased to submit the following proposal to produce a publicly available set of soil organic carbon GIS layers to help advance the understanding of soil health in projects and planning throughout the Commonwealth.

The HSAP, as you well know, identified soil organic carbon (SOC) as a key measurement of soil function and soil health. Many of the objectives of the HSAP require estimates of current and potential SOC in order to identify key locations of protection and intervention. Currently there are no publicly available GIS data layers to easily guide this work. However, this project, a collaboration between Regenerative Design Group, Maggie Payne - State Soil Soil Scientist NRCS Massachusetts and Vermont, and Dominique Pahlavan - EOEEA GIS Coordinator , seek to address this limitation through the production of two data layers: 1) Estimated Existing Soil Organic Carbon Stocks, and, 2) Potential Soil Organic Carbon.

Together, these layers allow for the identification of key SOC resources for protection, evaluation of potential impacts of protection and intervention, and evaluation of potential impacts of development and other land use changes.

Thank you for considering this proposal. We are happy to answer any questions you might have.

All the best,

Sebastian ‘Bas’ Gutwein

Operations Manager, Regenerative Design Group

Project Description

Introduction

The Massachusetts Healthy Soils Action Plan (HSAP) identified soil organic carbon (SOC) as a key indicator of soil function and soil health. Many of the objectives of the HSAP require estimates of current and potential SOC in order to identify key locations for protection and intervention. Currently there are no GIS data layers that achieve this. The US Natural Resources Conservation Service does provide estimates of SOC but these estimates do not take into account the primary dynamic driver of SOC: land cover. This project proposes to create GIS data layers that estimate the current and potential SOC of all soils in the Commonwealth. This will allow for the identification of key areas for protection and intervention, for evaluation of potential impacts of protection and intervention, and for evaluation of impacts of development and other land use change.

The NRCS provides SOC values as part of their gSSURGO product but those values do not account for the impact of land cover on SOC. As documented in the HSAP, land cover is a key determining factor in SOC stocks. An acre of forest is expected to have close to twice the SOC of an acre of cultivated land with the same soil type. To remedy this gap, our proposal is to provide GIS layers that take the impact of land cover on SOC into account.

In addition to the GIS layers we will provide a table of land cover conversion impacts on SOC as well as conduct and record a workshop for planners, conservation specialists, other staekeholders, and the general public on how to utilize these datasets to identify key soil carbon resources and the impacts of land cover change on SOC, soil function, and soil health. We will also present the production process and use of these layers at no fewer than three conferences.

Goals and Objectives

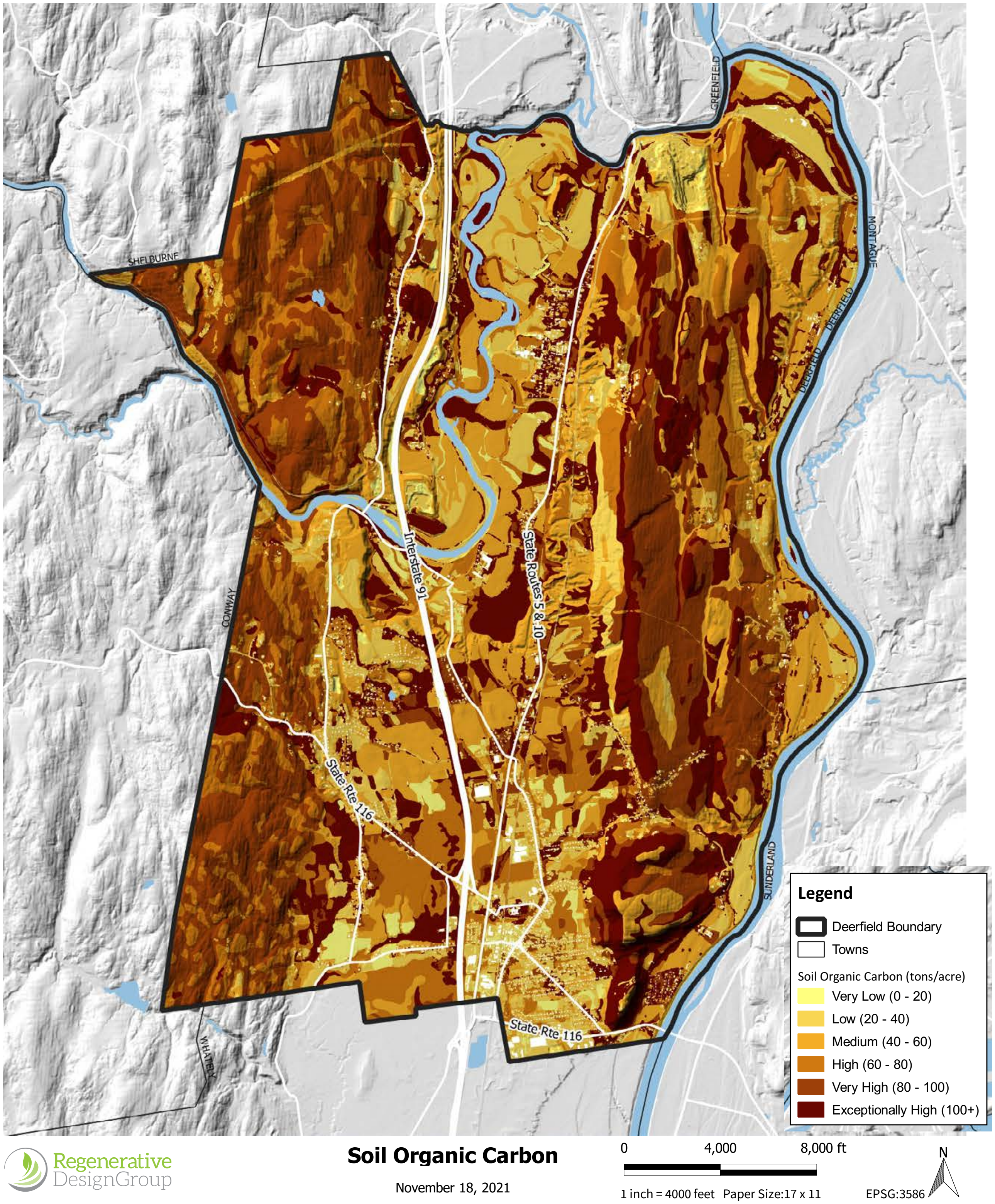
The goal of this project is to enable people in both the public and private sectors to understand and plan for soil carbon resources using high-resolution GIS layers. This meets the stated objective of the Healthy Soils Challenge Grant Initiative to "Refine Tools for Municipal Soil Mapping, Assessment + Planning".

The direct objectives of this project are to:

1. Produce three new GIS products consisting of
    a. Estimated Existing Soil Organic Carbon
    b. Estimated Potential Soil Organic Carbon
    c. A table for estimating impacts of land cover conversion
2. Provide documentation enabling GIS users to appropriately use these layers in analysis and planning
3. Work with EOEEA's GIS Coordinator to make these layers publicly available as rapidly as possible

Specific areas where this project will align with or advance the objectives of the HSAP:

Strategy #4 of the Massachusetts Healthy Soils Strategies (page 7 of HSAP) states that we must "Account for the Soil Organic Carbon Pools + Sequestration Capacity in all carbon accounting efforts". This project will directly address the ability to account for SOC pools by providing a vastly improved high resolution GIS layer of the existing Massachusetts SOC pools. By creating a high resolution SOC potential layer and land conversion SOC impact table we also improve the ability to estimate sequestration capacity. Additionally this project will allow for location specific estimates of other healthy soils project impacts. Having location specific estimates of project impacts will allow organizations attempting to advance the HSAP to evaluate and prioritize actions that will have the best effect on soil carbon and soil health. This data will support all of the other Healthy Soil Actions and Strategies defined in the Healthy Soils Action Plan.



Land Cover Adjusted Soil Organic Carbon Map deliverable from the Deerfield Healthy Soils Project. Produced by Regenerative Design Group. (2022)

Methodology

Because gSSURGO provides the best available estimates of SOC for state and municipal planning purposes, our approach takes these values as a starting point and calculates adjustments that account for the impact of land cover on SOC. Estimates for SOC will be a further refinement of the methods we have developed and used in our previous work for the commonwealth including HSAP, and Municipal Vulnerability Preparedness (MVP) projects such as the Apple Country Natural Climate Solutions Project, the Deerfield Healthy Soils Project, and the SuAsCo Natural Climate Solutions Project. Some of this process was documented in the 2022 *Soil Security* paper "Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts" (See Appendix #3). Figure 1 shows a simplified diagram of the inputs and products of the SOC GIS data layers production.

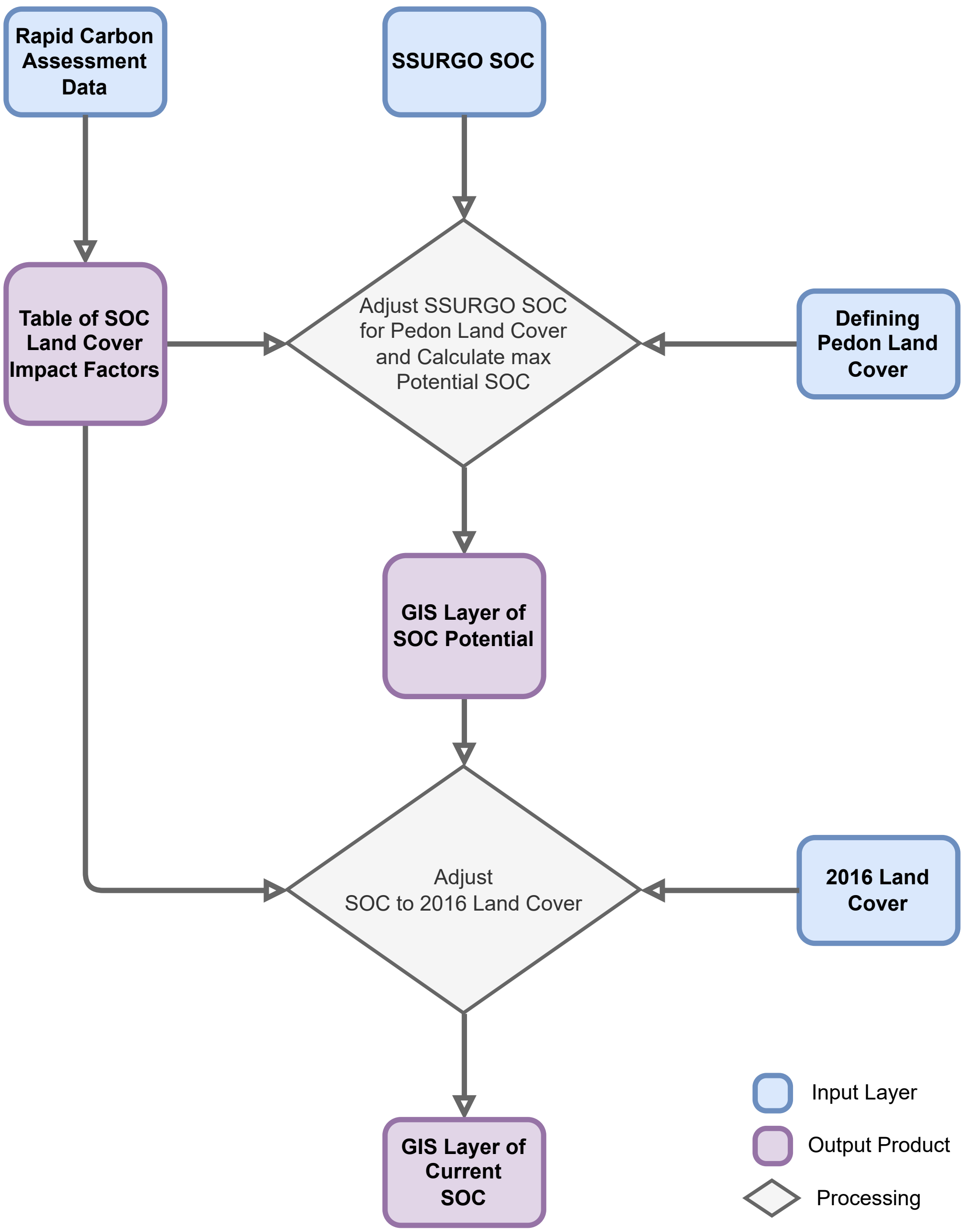


Figure 1. *Data processing inputs and outputs for estimating current and potential SOC levels*

1. Determine SOC Land Cover Impact Factor

To adjust the gSSURGO SOC values we must determine the impact that land cover has on SOC and calculate a land cover SOC impact factor that we can use to adjust SOC values. To determine the impact of land cover, we will use the NRCS's Rapid Carbon Assessment (RaCA) data. In 2010 the RaCA project tested SOC to 1 meter depth in over 6000 locations across the US. These sample areas also included the associated land cover. This extensive data will be used to determine the average difference between land covers. An earlier version of this process was used in the HSAP, and is documented in our *Soil Security* article (2022) (Appendix #3). For this project, we propose to improve SOC estimates by expanding the pool of data used to calculate the land cover SOC impact factor, by including all the RaCa points in the two USDA Major Land Resource Areas (MLRA) associated with MA, namely the Northeastern Forage and Forest Region and the Northern Atlantic Slope Diversified Farming Region. If there is a significant difference between the results for each MLRA, separate impact factors will be provided for each. While the process described here is suitable for the majority of land cover in MA, some land covers such as wetland and impervious surface will require other methods. The best approach to these land cover types will be determined in the course of this project. The end result will be a table of land cover conversion impact factors that will be used in estimation of current and potential SOC and provided as a product of this project.

2. Create an SOC Potential Layer

In northeast upland soils, the land cover with the highest SOC value is forest. Therefore to estimate Potential SOC, we calculate the SOC level that would be present under forest land cover for each soil type. To do this we must first determine what type of land cover characterized the defining pedon for each soil type when SSURGO established their canonical SOC value. Then, we apply the SOC impact factors calculated in the previous step to adjust the gSSURGO SOC values for each soil type to their expected SOC under forest. For soil types whose reference pedon was already forest, no adjustment is applied. We then apply these adjusted SOC values as weighted averages by area to SSURGO map unit polygons, to produce a layer of Potential SOC for the Commonwealth.

3. Create an Estimated Current SOC Layer

Using the gSSURGO SOC values, the land cover of the reference pedon, and the land cover SOC impact factors, we can also provide a better estimate of current SOC values. In the previous step we adjusted SOC values to reflect their expected levels under forest cover. In this step we adjust them to reflect their expected values under their current land cover. To do this we use the land cover designations found in the MassGIS 2016 Land Cover/Land Use layer to apply adjustments to those soil types whose reference pedons differ from present land cover. Then, as above, we apply these adjusted values as weighted averages to SSURGO maps unit polygons to create a statewide Estimated SOC layer.

4. Present the Process and Data Layers and Their Uses

Once the SOC estimation products have been created, RDG will present the process and key uses of the data as a workshop. This workshop will be recorded and an edited version of the recording will be made available to the public. We will also present this information at no fewer than 3 conferences

5. Provide a Method for Data Access to the Public

RDG will host the data layers on our website for up to three years. During that time we will work to find a more appropriate long term host for dissemination. We have reached out to MassGIS and have received encouragement from EOEEA GIS Coordinator Dominique Pahlavan that MassGIS would be a viable repository for the SOC layers. We would work with Dominique and others at the EOEEA and MassGIS to determine the appropriate GIS data types and resolution for hosting at MassGIS or another affiliated organization. We would like the final products to be as useful as possible and will therefore explore releasing them at multiple scales and aligned with other datasets such as gSSURGO and the 2016 High Resolution Land Cover datasets to make them accessible at both statewide and project site scales.

Expected Outcomes and/or Deliverables

There will be 4 deliverables for this proposed project:

1. A **table of land cover SOC impact factors** that represent conversion factors between the land covers classes in the 2016 High Resolution Land Cover dataset.
2. A **GIS layer** covering the extent of MA that represents the **SOC under the land cover with the highest SOC potential.** In upland soils in MA this is forest and in wetland soils this is wetland.
3. A **GIS layer** covering the extent of MA that represents the **estimated SOC** under the land cover identified by the 2016 High Resolution Land Cover dataset.
4. **A workshop** on how these layers were produced and how to utilize them for planning and analysis purposes. This workshop will be recorded and an edited version of the recording will be provided and made available to the public.

Proposed Budget

Contract Item	*Subtask*	Total Estimated Price
1: Project Initation & Initial Processing	1.1 Project Initiation	$ 3,000.00
	1.1 Project Kickoff Meeting with Advisors	$ 1,050.00
	1.1 Project Kickoff Meeting with State	$ 1,200.00
	1.2 Initial Data Processing	$ 27,750.00
	1.3 Mid-Project Meeting with Advisors	$ 1,050.00
	1.3 Verification and Documentation	$ 6,000.00
	1.4 Post Preliminary Data Layers	$ 7,000.00
1: Project Initation & Initial Processing Total		**$ 47,050.00**
2: Production of Final Data Layers & Workshop	2.1 Final Data Processing and Documentation	$ 6,000.00
	2.2 Post Final Data Layers	$ 6,000.00
	2.3 Workshop Production	$ 9,000.00
	2.4 Wrap Up Meeting with State	$ 1,050.00
2: Production of Final Data Layers & Workshop Total		**$ 22,050.00**
Grand Total		**$ 69,100.00**

The total budget for this project is **$69,100** with most of that being spent on Phase 1 of the project which wraps up by the end of June 2024. In addition to the workshop RDG is providing an in-kind match of **$10,000** that will cover the presentation of the use of the SOC GIS layers at no fewer than 3 conferences of likely SOC GIS users.

Budget line items were estimated by using our standard hourly rates:

Lead Analyst: $175/hr

Senior Associate: $150/hr

Associate: $125/hr

Organizational Capacity

Project Personnel and Roles

The team members for this project have substantial experience working together to deliver high quality products that reveal the patterns and processes of landscapes that planners need to make better decisions. For the past several years, Sebastian Gutwein has lead the team in developing innovative soil carbon estimation models that account for important factors that are not often considered. Expanded profiles and resumes for each team member are included in Appendix #2.

Sebastian Gutwein

Lead GIS mapping and analysis

Keith Zaltzberg-Drezdahl

Project management, coordination, and workshop development

Eric Giordano

Support GIS mapping and analysis, production, and coordination

Rafter Ferguson

Lead statistical analysis and research

Relevant Project Experience

Regenerative Design Group has conducted extensive work to understand and map soil function and soil organic carbon as lead-authors of the Massachusetts Healthy Soils Action Plan and several Municipal Vulnerability Preparedness grant projects. Below is a summary of some of this relevant work, with more extensive project descriptions for a selection of the projects provided in Appendix #1 - Project Examples.

Massachusetts Healthy Soils Action Plan, EOEEA (2023)

Regenerative Design Group were the lead authors of the MA Healthy Soils Action plan which explores the impact of land cover and land use change on soil health, soil function, and soil organic carbon. The plan enumerates priority strategies for each land cover type to preserve and promote healthier soils state wide and is the basis of these Healthy Soils Challenge Grants.

Apple Country Natural Climate Solutions Project, Municipal Vulnerability Preparedness Program (2021)

This MVP-funded project for Harvard, Devens, and Bolton provided RDG with the opportunity to downscale and refine their unique approach to estimating soil organic carbon quantities based on existing soil and landcover data for the municipal scale. As the lead geo-spatial analysts and soil health experts, RDG assisted BSC Group and Linnean Solutions to identify sites and projects for Nature-based Solutions.

Deerfield Soil Health Plan, Municipal Vulnerability Preparedness Program (2022)

As a town with abundant agricultural land, long term soil health is a major concern of Deerfield residents. RDG worked with town officials, farmers, schools, and other stakeholders to draft an action plan to preserve and promote healthy soils focused on the unique landscape of Deerfield. Mapping current and potential SOC levels and landcover were important contributions to determining priority recommendations. Along with the resulting report, RDG worked closely with Chris Curtis of Conservation Works to produce several draft byways to promote soil health that are currently being considered for adoption by the town. The project also included educational materials and a "soil health field day" event that was attended by over 120 high school students.

The Nashua River Communities Resilient Lands Management Project, Municipal Vulnerability Preparedness Program (2023)

RDG worked with the towns of Clinton and Bolton on the MVP funded project to identify sites and projects for nature based solutions. RDG and partners worked together with residents and landowners to define ways to care for and steward forests, open space, and wetlands through the Nashua River Communities Resilient Lands Management ("Nashua River") project. This project resulted in place-based land use and land management strategies that can enhance the potential of forests, open spaces, and wetlands – and the rules and regulations that shape them – to contribute to healthy, equitable, and thriving communities. This included substantial analysis of soil function in both towns.

Hudson-SuAsCo Nature-based Solutions Project, Municipal Vulnerability Preparedness Program (2024)

The SuAsCo Natural Climate Solutions project is a joint effort by stakeholders in the towns of Hudson, Framingham, and Natick with consultant partners from Regenerative Design Group, Linnean Solutions, and BSC Group to identify high impact sites for nature based interventions that will support the towns' climate resilience. This project has a strong focus on environmental justice and improving conditions for climate vulnerable populations. Demographic data was overlaid with other data on known ecological hazards to create a human health and vulnerability map that contributed to developing project priorities. With the understanding that soil health is foundational to the function of all terrestrial ecosystems, Regenerative Design Group lead an initial phase of the project to establish a baseline estimation of current soil health in the towns and analyze the effects existing land cover and management practices have on these resources.

Ayer/Devens Pocket Forest Pilot Project, Municipal Vulnerability Preparedness Program (2023)

The aim of the Ayer/Devens Pocket Forest project was to locate a series of suitable sites in Ayer and Devens for the establishment of small and very diverse forest plots that provide numerous ecosystem services. RDG provided a variety of mapping, analysis, assessment and design services throughout the project, including estimated soil organic carbon. In addition to this core role, our team assisted project partners BSC Group and Linnean Solutions to carry out a robust community engagement, planning, and design process. Sites were chosen based on a number of criteria including potential regeneration of soil organic carbon. The pilot phase of the project was completed with the planting of a demonstration site with more than 50 residents of Ayer and Devens.

No Net Loss of Carbon in Wetlands in Massachusetts, Massachusetts Department of Environmental Protection, Ongoing

RDG is currently working with BSC Group, Woodwell Climate Research Center, and the Massachusetts Association of Conservation Commissions to provide the MassDEP with a high-confidence estimate of wetland area and carbon stocks for the Commonwealth in service to the No Net Loss of Wetland Carbon goal established by the EOEEA. RDG has developed a machine learning process using the well-established Random Forest approach to identify unmapped wetlands in Massachusetts to provide a more accurate wetland carbon stock estimate. Additionally, our team is assisting Woodwell and BSC Group to determine the best process to estimate wetland carbon fluxes and project impacts.

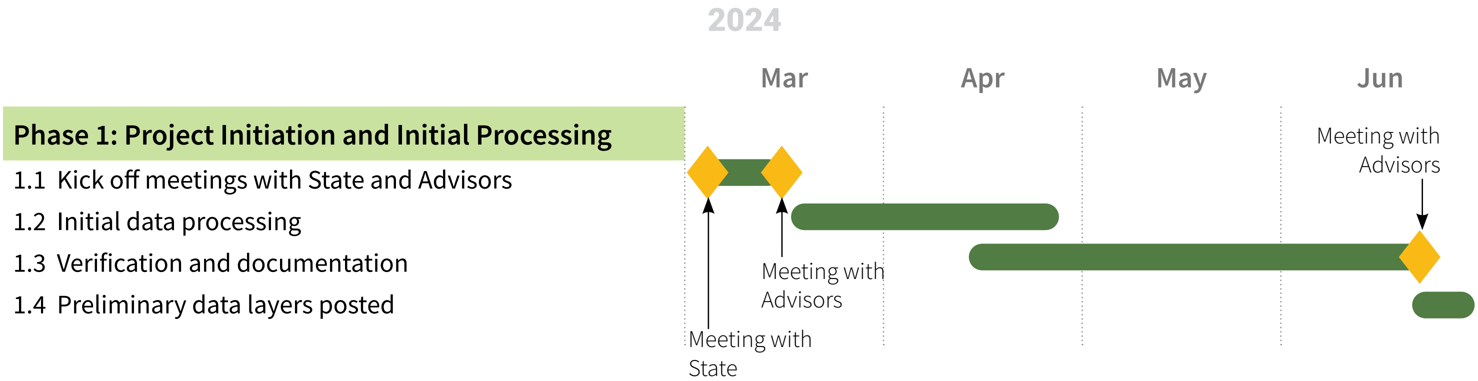
Fitchburg/Nashua River Watershed-Wide Nature-Based Solutions Project, Municipal Vulnerability Preparedness Program (2024)

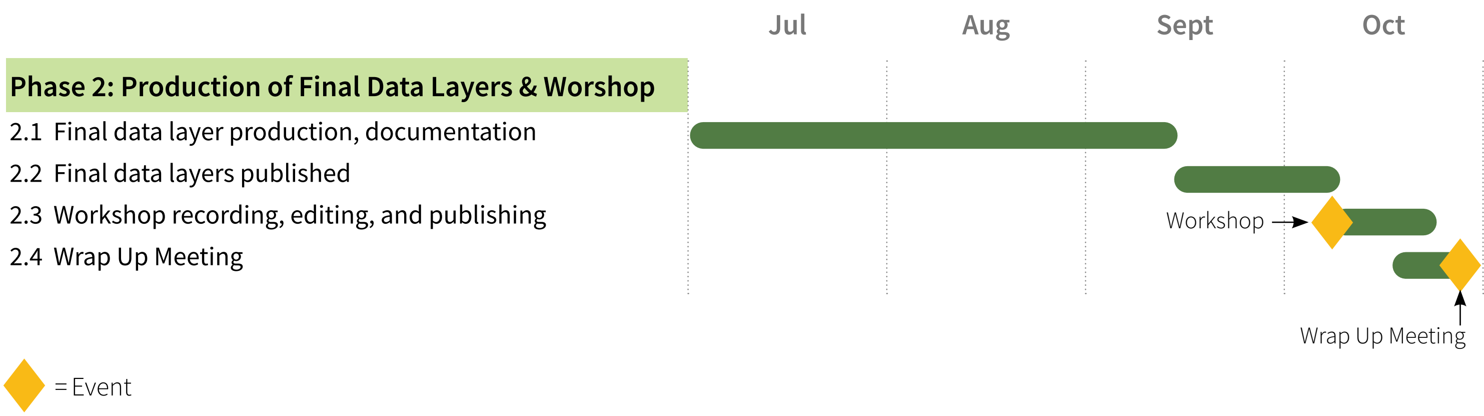
Regenerative Design Group (RDG) provided soil health mapping, analysis, and assessment services to support the Fitchburg/Nashua River Watershed-wide Nature-Based Solutions Project as a sub-consultant to the Nashua River Watershed Association (NRWA). Together, the maps, tables, figures, and the accompanying text produced by RDG will enable municipalities, individuals, businesses, schools and organizations throughout the watershed to grasp the overall regional distribution of soils and land cover types, and discern potential targets of opportunity where nature-based solutions can be most effectively deployed within the watershed.

Soil Productivity Assessment Project, The Trustees (2022)

RDG worked with Trustees' agriculture and conservation staff in collaboration with American Farmland Trust to provide soil health baseline assessments and stewardship plans for seven farms located in central and eastern Massachusetts. Regenerative Design Group developed a flexible integration of a custom geodatabase and mobile applications to enable Trustees' staff to capture and track lab-based soil results and field observations over time. This database will allow the Trustees to evaluate the soil health impacts of practice modifications, including soil organic carbon fluxes.

Proposed Project Timeline





Project Evaluation and Monitoring

Our products will be evaluated by state officials and our advisors during the verification and documentation steps of both Phase 1 and Phase 2. Maggie Payne, the NRCS Massachusetts State Soil Scientist has agreed to be an advisor and peer reviewer for this project. Additionally EEA GIS Coordinator Dominique Pahlavan has agreed to assist in advising on the GIS layers as they pertain to adoption by MassGIS.

We will also use specific data points from the Rapid Carbon Assessment to validate our model. The RaCA data contains SOC measurements from points in Massachusetts. We will compare the measurements of those points with our predicted SOC to determine the level of accuracy of our estimations.

Finally, our entire process will be documented and published for peer review.

Sustainability Plan

Post grant project sustainability assessment

We feel that the post grant sustainability is very high but we will address the sustainability of each of the deliverables separately below.

The **table of conversion factors** should be useful and significant for a long period of time. Even if new data and better processes for measuring and estimating the impact of land cover on SOC are developed this product will continue to be useful for comparison purposes and can be adjusted to account for new estimates.

The **SOC Potential Layer** should also be useful and significant for a long time period. In part this is because it will be connected to the SSURGO and gSSURGO datasets and the SOC values contained in the layer are based on the inherent properties of the soil that are unlikely to change. It will also be easily updated as the SSURGO data is updated.

The **Estimated Current SOC Layer** is the layer most likely to have a short useful life. This is because it is based on the MA 2016 High Resolution Land Cover dataset and unlike inherent soil properties the land cover is constantly changing. In fact it is expected that an update to the High Resolution Land Cover dataset will be released in the near future. Unfortunately the release is unlikely in the time frame of this project. However that does not mean that the Estimated Current SOC Layer based on 2016 data will not be useful in the future. A 2016 SOC estimation along with an updated SOC layer based on more recent data will allow for estimations of SOC gains and losses over that time period which would be a very valuable planning tool.

The data formats we will be delivering the GIS layers in will be in industry standard open formats that are unlikely to become obsolete in the near future.

Partners involved and role: Regenerative Design Group will be conducting the design and production of the data layers and associated products. These products will be evaluated by state officials and our advisors during the verification and documentation steps of both Phase 1 and Phase 2. Maggie Payne, the NRCS Massachusetts State Soil Scientist has agreed to be an advisor and peer reviewer for this project. Additionally EEA GIS Coordinator Dominique Pahlavan has agreed to assist in advising on the GIS layers as they pertain to adoption by MassGIS.

Community engagement will consist of targeted outreach to select planners and conservation specialists for both the production of the data layers and delivery of workshops.

Risk Assessment for Project, Partners, & Timeline

The members of this team and our partners have an excellent track record of delivering high-quality experiences and work products on-time and on-budget. The attached resumes and project qualification sheets provide documentation of these work products and the high degree of qualification we bring to this project, including numerous professional certifications, advanced degrees, and decades of professional experience. It is notable to mention that two of the larger projects, HSAP and the Apple Country Natural Climate Solutions project, spanned the beginning of the COVID pandemic. This required a hard pivot to remote or distanced options in outreach, education, and field-based events. The success of these projects gives us confidence that we can navigate unforeseen challenges. We have identified the following risks and mitigation strategies for the completion of the project:

Staffing changes/disruptions

- Our team has a deep bench of staff that could step in should unexpected disruptions require a change of project staffing. In anticipation of this potential we will hold regular project meetings internally with understudies and construct a resilient accessible file sharing system.

Tasks take longer than expected

- Should tasks take longer than expected, we have the capacity to pull in additional staff to ensure that key deadlines are met, as well as a solid track record of delivering high caliber work products on time.

COVID Resurgence / Other Pandemic

- While in person and hybrid events are planned for this project, all events will be designed to allow for remote and asynchronous engagement. Recorded sessions will also serve as resources for future outreach and education.

In summary, we put forward this proposal as a low risk investment due to the capacity of or firm and the ability to deliver this scope of work within this budget and without requiring additional third party funds for completion.

Appendices

Appendix 1: Project Examples

Massachusetts Healthy Soils Action Plan

CLIENT

Massachusetts Executive Office of
Energy + Environmental Affairs, 2019-2023

SERVICES + ACCOMPLISHMENTS

Analysis and modelling of Soil Organic Carbon (SOC) stock, segmented by land cover type

Projection of 2050 SOC flux, based on land cover change

Soil-smart planning and management priorities

Stakeholder engagement

Management of 40 person working group

PROJECT OVERVIEW

The Massachusetts Healthy Soils Action Plan (HSAP) is the nation's first effort to understand, protect, and revitalize soil function in all land uses statewide. This Plan, commissioned by Massachusetts Executive Office of Energy and Environmental Affairs, reveals the tremendous impact land use and management has on the soils of the Commonwealth and sets forth strategies and actions to increase soil health as a way to improve food security, ecosystem function, and climate resilience across the region.

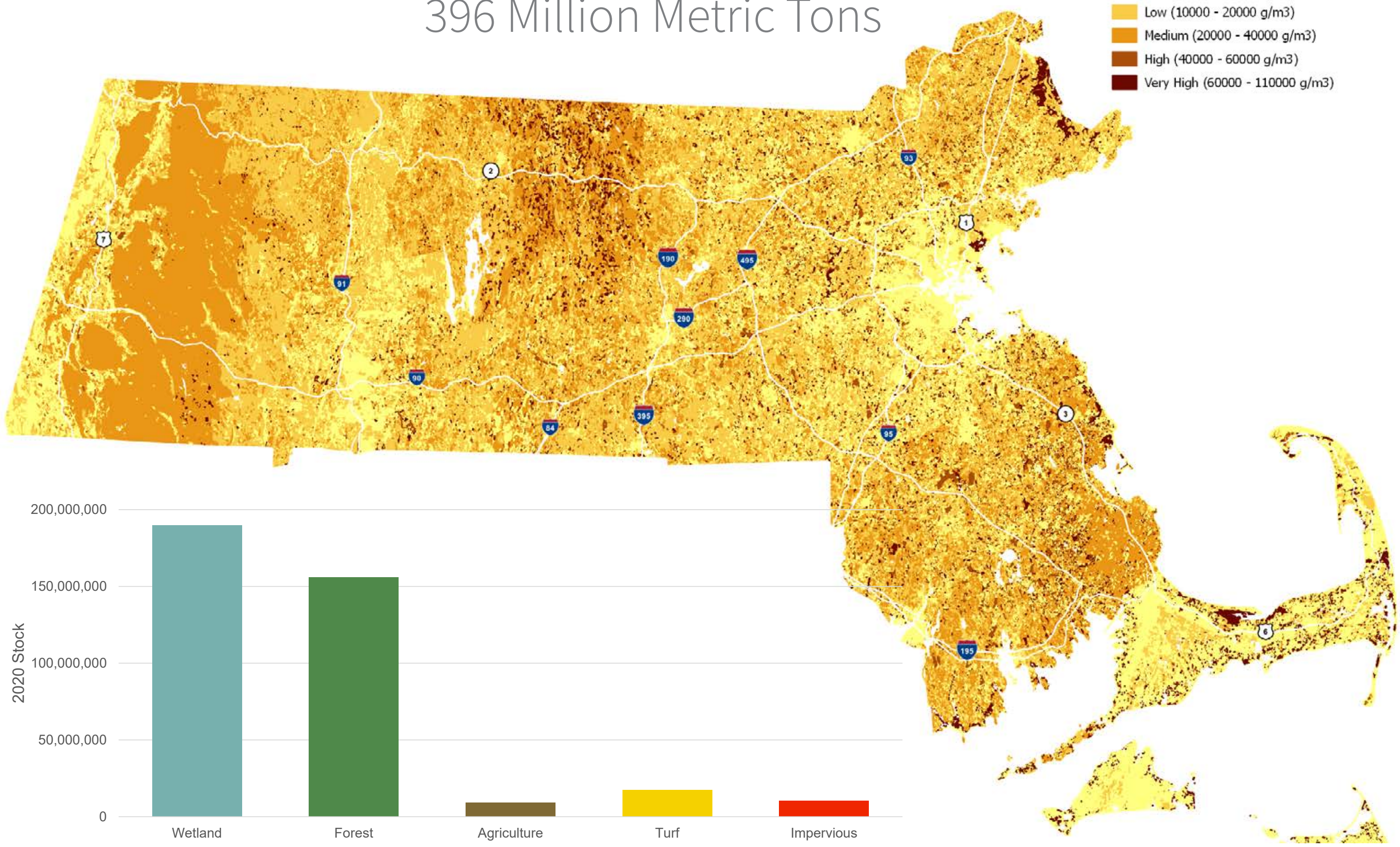
Through an 18-month process the consultant team, led by Regenerative Design Group, conducted a detailed literature review and geospatial analysis to understand the key factors and dynamics that shape soil health. This included the development of a novel method for quantifying soil organic carbon (SOC) based on land cover and drainage classification.

With guidance and review of a 40-member Working Group, representing state and federal agencies, conservation organizations, scientific advisors, and community stakeholders, RDG developed a series of evidence-based strategies and actions aimed at transforming the impact of soil management on climate from a negative to a positive.

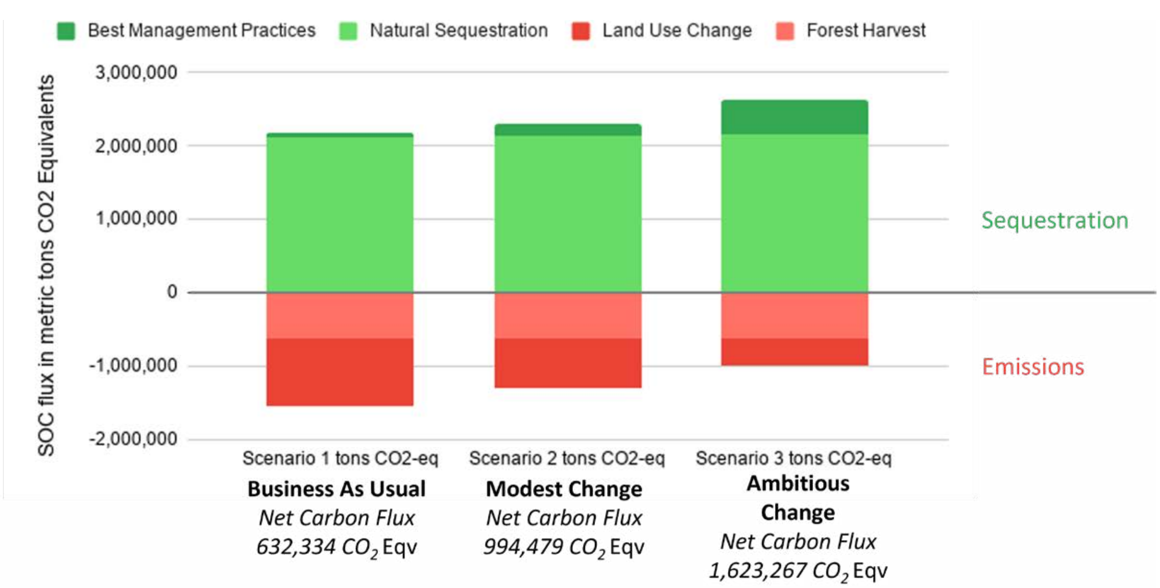
The result is a roadmap for policymakers, land managers, and soil health advocates to understand the interconnected nature of the Commonwealth's landscapes and the role they play in soil carbon sequestration and climate resilience.

Regenerative
DesignGroup

Massachusetts Soil Organic Carbon Stocks
396 Million Metric Tons



2050 Comparison of Annual Soil Organic Carbon Fluxes



Apple Country Natural Climate Solutions Project

CLIENT

Towns of Bolton + Harvard with Devens Regional Enterprise Zone Massachusetts Municipal Vulnerability Preparedness Program, 2019

SERVICES + ACCOMPLISHMENTS

Refined method for modeling soil organic carbon using land cover

Analysis and modelling of soil organic carbon stocks, segmented by land cover type

Projection of annual soil organic carbon fluxes for 2050 based on land use change predictions

Development of soil-smart planning and management BMPs

PROJECT OVERVIEW

In a regional effort to address the challenges of climate change, biodiversity loss, and regional development pressures, the towns of Bolton, Harvard, and Devens engaged BSC Group, Linnean Solutions, Woodwell Climate Research Center, and Regenerative Design Group to identify regional vulnerabilities and recommend nature-based climate solutions (NbS) that will increase the resiliency of their communities and ecosystems.

Nature-based Solutions provide cost-effective climate resilience by providing multiple co-benefits, including reduction of greenhouse gas emissions, improved water quality and water supply, reduced flooding, improved air quality, cooler local temperatures, fish and wildlife habitat and support for biodiversity, recreational and aesthetic opportunities, and improved physical and mental public health.

Regenerative Design Group led the mapping and analysis of soil carbon components of this project and contributed to the identification of nature based solutions to increase regional climate resilience. To assist the communities to understand the impact of land use on health of their soils and contributions to climate resilience, RDG remapped NRCS soil carbon based on land cover (top right) and created an infographic of projected soil organic carbon fluxes in 2050 (bottom right).

LINNEAN SOLUTIONS

Regenerative DesignGroup

Land Cover Adjusted Soil Organic Carbon

When adjusted for land cover, the total stock of SOC in Apple Country increased from 2.2 million metric tons (SSURGO) to 2.8 million metric tons, a difference of 400,000 tons.

This work suggests that the amount of carbon stored in the soils of this region is underestimated, diminishing the significance of conserving and regenerating forests and wetlands.

These maps reveal how land cover directly impacts the SOC.

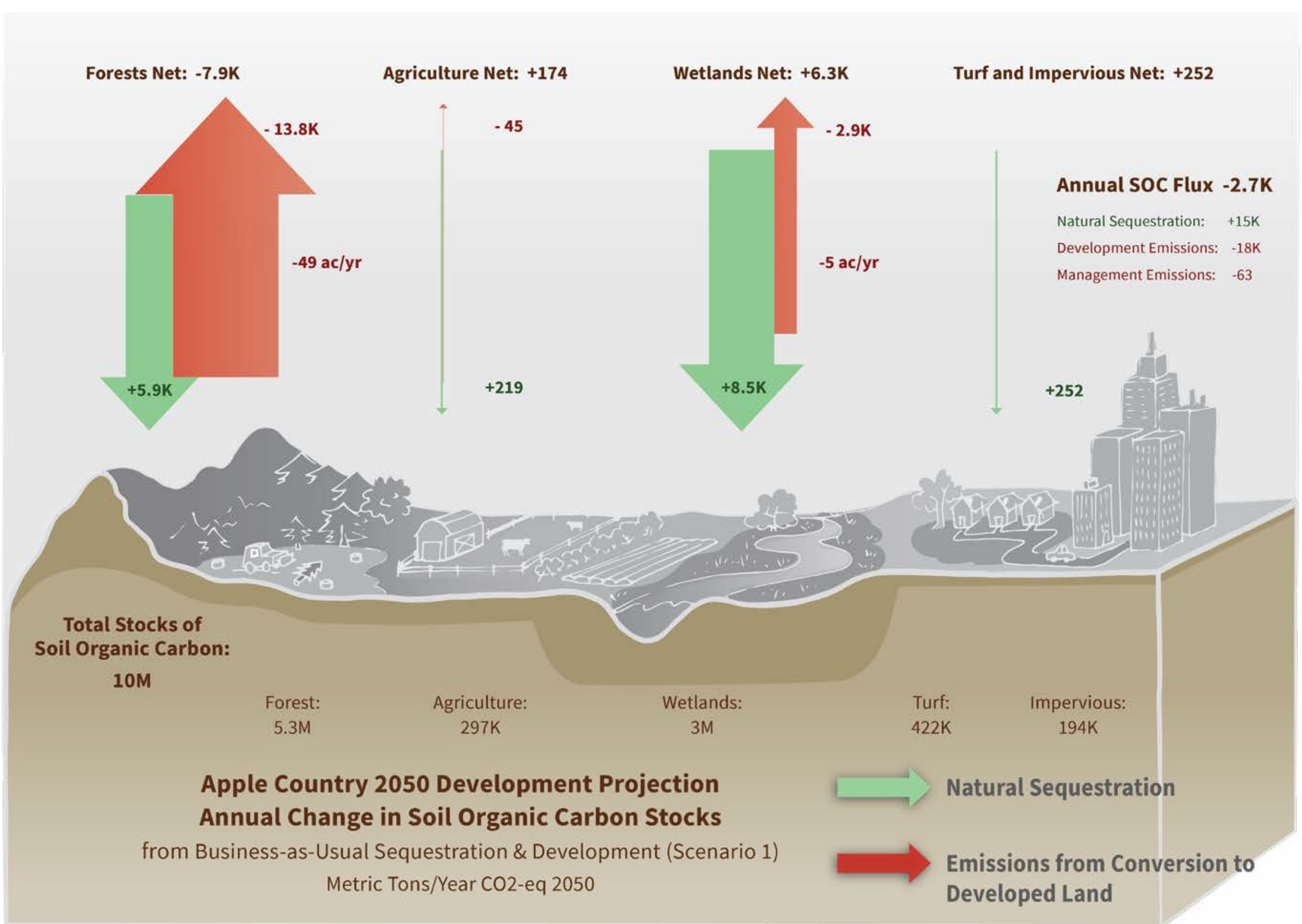
ORIGINAL SSURGO SOC

2.2 Million Metric Tons

LAND COVER ADJUSTED SOC

2.8 Million Metric Tons

2050 Soil Organic Carbon Fluxes



SuAsCo Nature Based Solutions Project

CLIENT

Towns of Hudson, Framingham, and Natick, Municipal Vulnerability Preparedness Program, 2022-2024

SERVICES + ACCOMPLISHMENTS

Analysis and modelling of Soil Organic Carbon (SOC) stock

Projection of 2050 SOC flux, based on land cover change

Soil-smart planning and management priorities

Selection of and recommendations for high-impact locations for nature based solutions

Focus on environmental justice and climate vulnerable populations

LINNEAN SOLUTIONS

Regenerative DesignGroup

PROJECT OVERVIEW

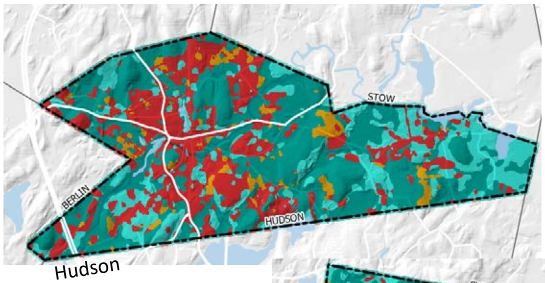
Launched in the fall of 2022, the SuAsCo Natural Climate Solutions project is a joint effort by stakeholders in the towns of Hudson, Framingham, and Natick with consultant partners from Regenerative Design Group, Linnean Solutions, and BSC Group to identify high impact sites for nature based interventions that will support the towns' climate resilience.

This project has a strong focus on environmental justice and improving conditions for climate vulnerable populations. Demographic data was overlaid with other data on known ecological hazards to create a human health and vulnerability map that contributed to developing project priorities.

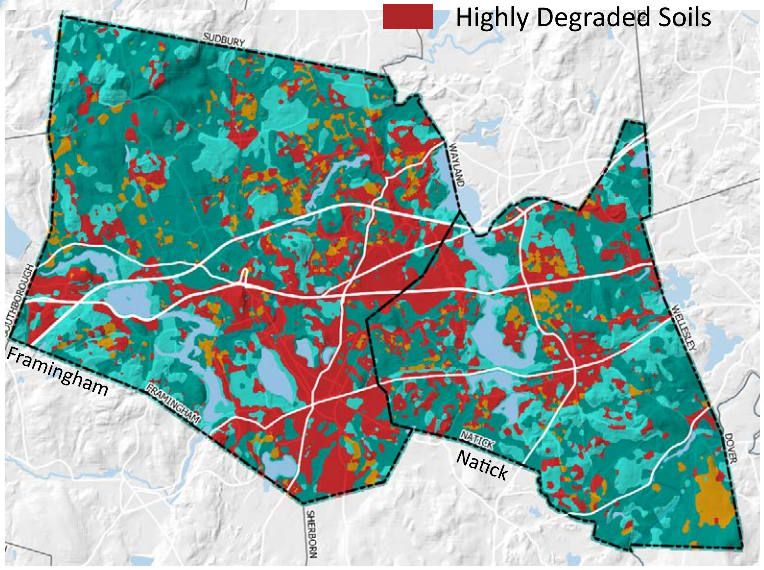
With the understanding that soil health is foundational to the function of all terrestrial ecosystems, Regenerative Design Group lead an initial phase of the project to establish a baseline estimation of current soil health in the towns and analyze the effects existing land cover and management practices have on these resources. The findings were summarized in a series of maps entitled Soil Functions for Resilience (top right).

From this baseline, the team completed an analysis that combines RDG's refined soil carbon predictions with other ecological data to map ecological planning priorities. The result is a map of planning districts (bottom right) with different priorities (e.g. restore and transform or plan and manage for resilience). Recommended actions for each district and an analysis of ideal candidate sites are major products of this project. Proposed sites for nature based solutions will receive a multi-stage assessment of vegetative health by drone monitoring.

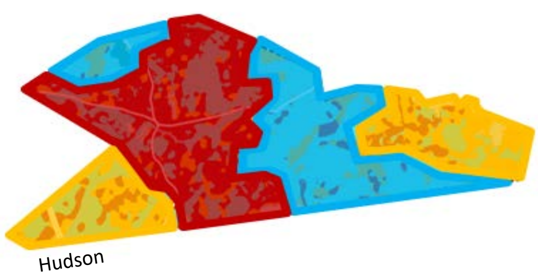
Soil Functions for Resilience



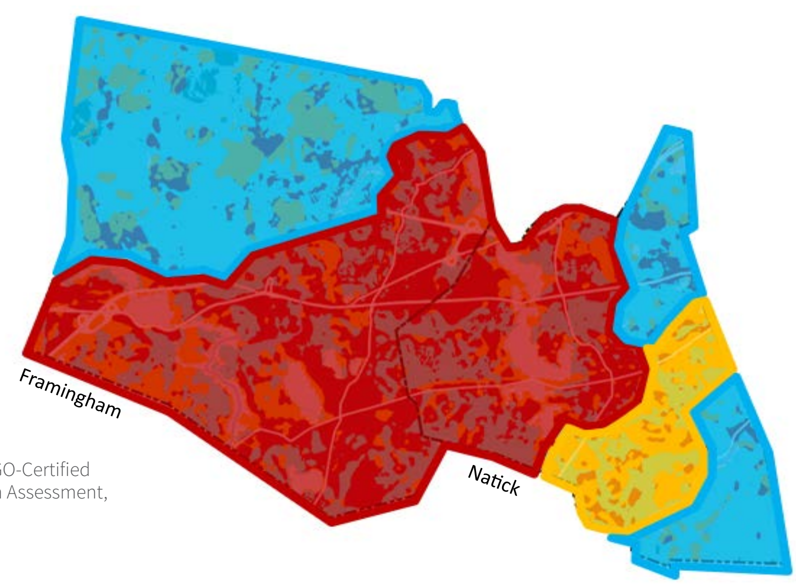
- High Performance Soils & High Carbon Soils
- Average Function Soils
- Degraded Soils with High Regeneration Potential
- Highly Degraded Soils



Ecological Planning Priorities



- Restore & Transform
- Plan & Manage for Resilience
- Intensive Intervention



Data Sources: Soils SSURGO-Certified NRCS, NRCS Rapid Carbon Assessment, MassGIS 2016 Landcover

Deerfield Soil Health Plan

CLIENT

Town of Deerfield
Municipal Vulnerability Preparedness Program, 2022

SERVICES + ACCOMPLISHMENTS

Analysis and modelling of Soil Organic Carbon (SOC) stock, segmented by land cover type

Soil-smart planning and management priorities

Stakeholder engagement

Sample bylaws aimed at protecting and improving soil resources

Soil sampling across a variety of land types providing the basis for future soil health tracking

Design and execution of a "soil health field day" for 120 high school students

Regenerative DesignGroup

PROJECT OVERVIEW

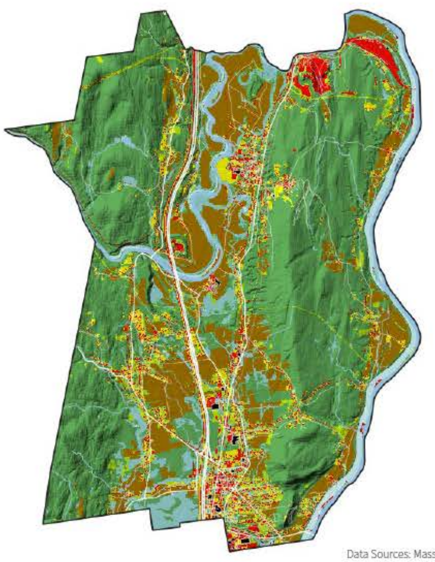
The Deerfield Healthy Soils Project is based on the premise that protecting and improving soil function across land uses is an essential component of climate-resilient planning. The overall goal of this project was to identify the most impactful actions and strategies that the community of Deerfield, Massachusetts can implement to steward its soils in ways that support the myriad of co-benefits and beneficial functions of healthy ecosystems including enhanced carbon sequestration and storage, greater fertility, and improved water dynamics.

Over the course of a year, Regenerative Design Group led a process that included high resolution modeling of Deerfield's current healthy soil resources; presentations, workshops, and conversations with stakeholders with a special focus on farmers considering the town's large agricultural community; soil sampling across a variety of land types providing the basis for future soil health tracking; a "soil health field day" for 120 high school students; and the development of several recommendations for potential bylaw improvements aimed at protecting and improving soil resources.

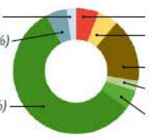
This project was completed in 2022 as part of a larger Municipal Vulnerability Preparedness action in the town of Deerfield, MA. Regenerative Design Group (RDG) worked closely with Chris Curtis (Conservation Works) who was the lead planner for the larger MVP project and who was the lead author of the sample bylaws included in our report. The consultants reported directly to Deerfield's Climate Change and Energy Committee in carrying out the work of the project.

Land cover + Soil Organic Carbon Stocks in Deerfield, MA

Landcover

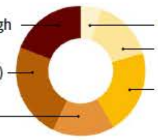


Forest	12,525 ac
Agriculture	3,506 ac
Wetland	1,160 ac
Turf & Landscaped Areas	1,123 ac
Trees	1,041 ac
Impervious	965 ac
Grassland or Shrub	571 ac
Open Water	527 ac

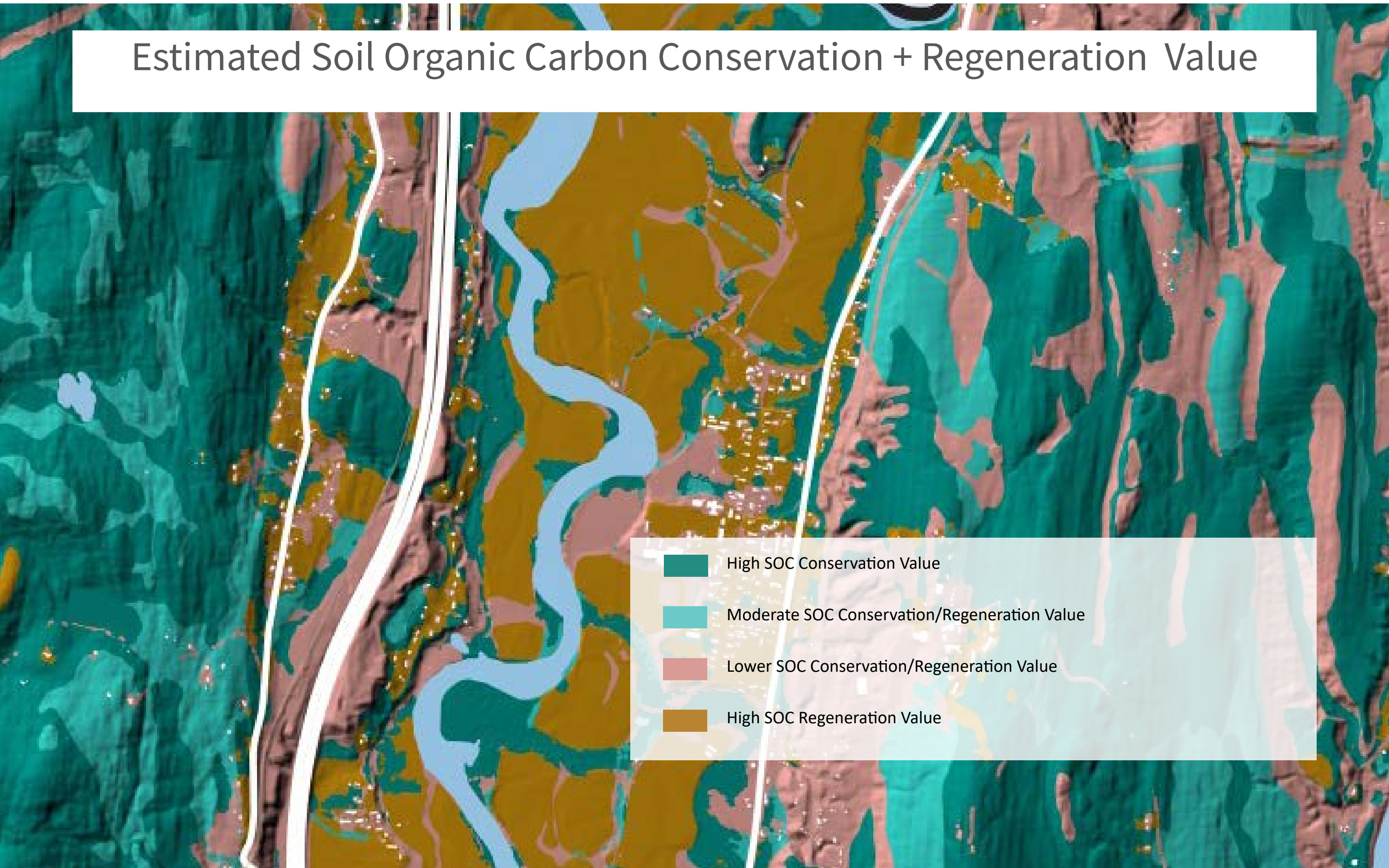


Predicted Soil Organic Carbon

Very Low (0-20 tons/acre)	1,120 ac
Low (20-40 tons/acre)	3,299 ac
Medium (40-60 tons/acre)	4,481 ac
High (60-80 tons/acre)	3,306 ac
Very High (80-100 tons/acre)	5,107 ac
Exceptionally High (100+)	4,097 ac



Estimated Soil Organic Carbon Conservation + Regeneration Value



Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts

CLIENT

Journal of Soil Security, 2022

SERVICES + ACCOMPLISHMENTS

Meta-analysis of scientific literature on soil organic carbon in various land cover types

Development of land cover SOC averages

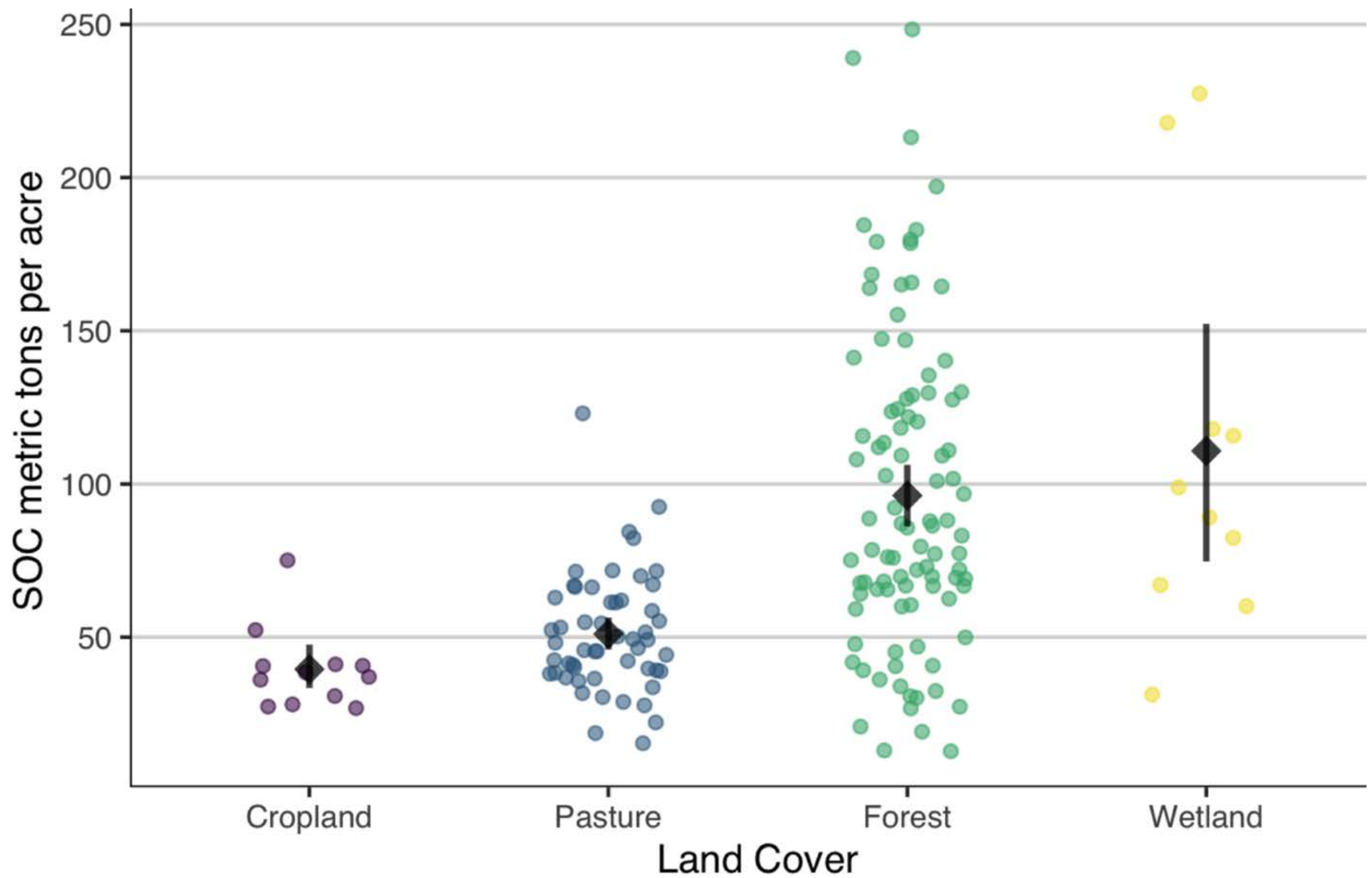
Estimation of total SOC statewide SOC stocks for Massachusetts

ABSTRACT

Land management and land cover change exert a strong influence on soil organic carbon (SOC) storage. As scientific, political, and business communities increase their awareness of the essential roles SOC plays in climateregulation and ecosystem functions, efforts to quantify the impacts of land use and anagement on SOC have increased rapidly. Existing methods of estimating SOC stocks from widely available data do not account for land cover, and are therefore of limited usefulness in understanding the impacts of past and future land use change.

This project explores a method of linking land cover to SOC using data from public datasets and the scientific literature, to provide an SOC Inventory for Massachusetts, and compares the results to those derived from a common baseline approach. Our method derives average land cover SOC values by combining data from the USDA-NRCS Rapid Carbon Assessment and the National Cooperative Soil Characterization Database with values from a meta-analysis of scientific literature. These are applied to the total area of the 20 most abundant landcover classes of Massachusetts. We compare this land cover-based approach with a baseline using SOC values found in the Soil Survey Geographic Database (SSURGO), applied to each soil map unit found within Massachusetts.

Our approach produced an estimated stock of 481 million metric tons of SOC, 109 million metric tons greater than the SSURGO baseline. We use these estimates to explore the use of the land cover based SOC values to project the impacts of likely land cover change by 2050.



CONTEXT + KEY FINDINGS

After the completion of the Massachusetts Healthy Soils Action Plan, members of RDG's consulting team published an article on the novel approach to estimating soil organic carbon at the state or larger regional scale.

Figure 3 (above) graphs the SOC mt/ha to a 1 meter depth for 172 samples tested by the National Resource Conservation Service from within 100 miles of the Massachusetts border. Cropland

An exerpt from Table 1 (right) contains the average SOC values for each major land cover type found in Massachusetts.

2016 High Resolution Land Cover Class	Average Soil Organic Carbon MT ha 1m depth	Source of SOC Value
Impervious (2)	54	Meta-analysis/ SSURGO
Developed or Open Space (5)	99	Meta-analysis/ SSURGO
Cultivated Crops (6)	81	RaCA/SCDB
Pasture or Hay (7)	126	RaCA/SCDB
Grassland or Herbaceous (8)	113	RaCA/SCDB
Deciduous Trees- non forest (9)	54	Meta-analysis/ SSURGO
Evergreen Trees- non forest (10)	54	Meta-analysis/ SSURGO
Forest (11)	214	RaCA/SCDB
Scrub/Shrub (12)	121	Meta-analysis/ SSURGO
Palustrine Forested Wetland (13)	825	RaCA/SCDB
Palustrine Scrub/Shrub Wetland (14)	825	RaCA/SCDB
Palustrine Emergent Wetland (Persistent) (15)	825	RaCA/SCDB
Estuarine Forested Wetland (16)	398	Meta-analysis/ SSURGO
Estuarine Scrub/Shrub Wetland (17)	398	Meta-analysis/ SSURGO
Estuarine Emergent Wetland (18)	398	Meta-analysis/ SSURGO

Appendix 2: Team Member Profiles and Resumes

Regenerative DesignGroup

Keith Zaltzberg-Drezdahl

MANAGING DIRECTOR, HEAD OF PLANNING, WORKER-OWNER

Keith is a founding partner of Regenerative Design Group. His approach to design is grounded in understanding the ecological and social potential of place, rigorous analysis, and systematic assessment. Keith combines this approach with on-the-ground skills and a strong social justice mission to create landscapes that are rooted in place and community. He is a lecturer and instructor on permaculture design, urban agriculture, resilience planning and food systems. Keith has taught at The Conway School and Smith College and holds a BS in Environmental Design from UMass-Amherst.

FOCUS AREAS

- Landscape Carbon Accounting & Planning
- Resilience Planning & Adaptive Design
- Soil Resource Planning
- Regenerative Agriculture & Urban Farm Design
- Project Management

TECHNICAL SKILLS

- GIS Mapping and Analysis
- AutoCAD
- Adobe Creative Suite

LECTURES + WORKSHOPS

- Soil Organic Carbon Estimation. Soil Science Society of America.
- Developing Healthy and Resilient Communities: A Case Study. Architecture Boston Expo
- Regenerative Design for Change Makers, Omega Institute

SELECTED PROJECTS

MA No Net Loss of Carbon in Wetlands | MassDEP

Development of a wetland mapping approach based on machine learning that identifies previously ambiguous wetlands. This project aims to identify innovative strategies, approaches, concepts, and regulatory recommendations to achieve No Net Loss of Carbon in Wetlands in Massachusetts. Project team includes BSC Group, the Massachusetts Association of Conservation Commissions (MACC), and the Woodwell Climate Research Center.

Nashua River Resilient Lands Management | Clinton and Bolton, MA

MVP Project. Development of management and stewardship guides and identification of leverage points for town bylaws changes to increase the resilience and functioning of important landscapes and ecosystems in Clinton and Bolton.

Soil Health Assessment | Deerfield, MA

MVP Project. Analysis of exisiting soil function by land cover and assessment of vulnerabilities and opportunities for soil health. Scope included healthy soils workshops and outreach events. *2022 Sustainability + Resiliency Award from the American Planning Association - Massachusetts Chapter*

Soil Health Productivity Assessment & Planning | Trustees of Reservations

Collaborated with American Farmland Trust to assess field-specific soil health and whole-site ecological health of seven Trustees farm properties. Designed and facilitated three workshops for Trustees staff and land managers. Final report included recommendations for soil health management, agroecological interventions and a discussion of trade-offs.

Climate Resiliency and Carbon Planning | Apple Country, MA

MVP Project. Worked with BSC Group and Linnean Solutions to assess and analyze ecological resources, and provide recommendations for nature-based solutions in the Towns of Bolton and Harvard and the Devens Regional Enterprise Zone. Extensive mapping, community outreach, site walks, and soil health assessments.

Soil Resource Assessment & Planning | Massachusetts Healthy Soil Action Plan

Project lead coordinating a 10-person project team and 50-person working group in GIS-analysis, scientific literature review, expert interviews, and broad stakeholder engagement to develop a comprehensive Healthy Soils Action Plan for all major land uses in Massachusetts. *2023 Special Recognition Award for Significant Value to Landscape Architecture from the Boston Society of Landscape Architects*

Greenhouse Gas Environmental Impact Assessment | Massachusetts Environmental Policy Act Office

Provided QAQC and technical team support in the development of a model to estimate greenhouse gas emissions and carbon sequestration loss from tree clearing associated with proposed expansion of a utility right of way.

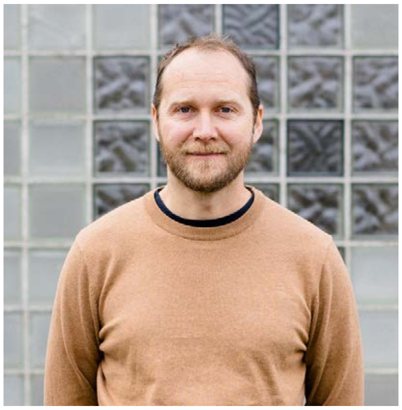
Regenerative Land Use Experiment | Major Northeast Utility Company

Assessment of potential for additional carbon sequestration through innovative land and vegetation management practices on ROW lands across three state for a major utility. Led in-depth study of current land cover, carbon stocks, and management practices to develop high level toolkits for land management teams.

SELECTED PUBLICATIONS

Gutwein, S., Zaltzberg-Drezdahl, K., Toensmeier, E., & Ferguson, R. S. (2022). Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts. Soil Security, 9, 100076. https://doi.org/10.1016/j.soisec.2022.100076

Regenerative DesignGroup



Sebastian Gutwein

Managing Director, GIS Specialist, Worker-Owner

Sebastian is a living systems designer whose extensive experience draws from the arts, ecology, politics and place. His understanding of how things work and how they interrelate allow him to design and plan for challenges that range from water conveyance to agricultural programming to complex GIS analysis and construction management. Since 2015, Sebastian has been the Land Surveying and Digital Design Instructor at The Conway School. He is currently in the GeoDesign Program at Penn State.

FOCUS AREAS

- Site Design & Planning
- Solar Site Design & Housing Layout
- Resilience Planning & Adaptive Design
- Whole Systems Integration
- Landscape Analysis & Assessment
- Food Systems Evaluation & Design
- Implementation, Construction & Project Management

TECHNICAL SKILLS

- Digital Rendering
- GIS Analysis + Assessment
- Document Production & Design
- Land Surveying

SELECTED PROJECTS

MA No Net Loss of Carbon in Wetlands | MassDEP

Lead data and GIS analyst for a wetland mapping approach based on machine learning that identifies previously ambiguous wetlands. This project aims to identify innovative strategies, approaches, concepts, and regulatory recommendations to achieve No Net Loss of Carbon in Wetlands in Massachusetts. Project team includes BSC Group, the Massachusetts Association of Conservation Commissions (MACC), and the Woodwell Climate Research Center.

Soil Resource Assessment & Planning | Commonwealth of Massachusetts

Lead data and GIS analyst. Developed novel, data-driven model for quantifying statewide soil organic carbon stocks and impact of land cover change on soil carbon.

Municipal Vulnerability Preparedness Projects: Soil Resilience Planning | Various Municipalities, MA

Lead data and GIS analyst. Development of unique and comprehensive models that combine soil and other ecological data with social and cultural information to identify high impact locations for nature based solutions for climate resilience. Mapping and research support for community engagement workshops and outreach events.

Greenhouse Gas Environmental Impact Assessment | Massachusetts Environmental Policy Act Office

Land use and carbon analyst. Directed development of environmental impact assessment model for greenhouse gas emissions and carbon sequestration loss from tree clearing associated with proposed expansion of a utility right of way.

Regenerative Land Use Experiment | Major Northeast Utility Company

Land use and carbon analyst. Assessed potential for additional carbon sequestration through innovative land and vegetation management practices on ROW lands across three state for a major utility. Conducted in-depth study of current land cover, carbon stocks, and management practices to develop high level toolkits for land management teams.

SELECTED PUBLICATIONS

Gutwein, S., Zaltzberg-Drezdahl, K., Toensmeier, E., & Ferguson, R. S. (2022). Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts. Soil Security, 9, 100076. https://doi.org/10.1016/j.soisec.2022.100076

Rafter Ferguson

Senior Researcher

Rafter focuses on research, education, and training for integrating agroecology, racial equity, and full-spectrum social justice. He specializes in participatory research and design, quantitative and qualitative data analysis, popular education, agroforestry, climate change mitigation and adaptation, and grassroots farmer-centered development.

ADDITIONAL SKILLS

- Group facilitation + public speaking
- Multivariate statistics, data analysis, and visualization with R/RStudio (including dimension reduction, clustering, bootstrapping, and Bayesian and frequentist multilevel modeling)
- Other software: Google Drive Suite, Microsoft Office Suite, iWork Suite

PROFESSIONAL EXPERIENCE

Interlace Commons | 2022-Present

Justice, Equity, and Diversity Consultant

- Qualitative research with BIPOC farmers to address barriers to agroforestry adoption
- Co-author of report "From the Roots Up: Centering racial justice to build transformative agroforestry" (with Ruth Tyson)
- Co-author of curriculum for technical service providers "Working with People, Working Across Difference: Social Competencies to Grow Agroforestry" (with Ruth Tyson)

Union of Concerned Scientists Washington, DC | 2018-2021

Scientist, Food and Environment Program

- Research, communication, and advocacy bridging agroecology and sustainability with farmer-centered equity issues
- Build and manage relationships with grassroots coalition partners with a focus on BIPOC-led and -centered organizations
- Authored high-impact blogs including "Why We Can't Separate Justice and Sustainability in the Food System" and led reports including "Losing Ground: Farmland Consolidation and Threats to New Farmers, Black Farmers, and the Future of Farming" and on the "Farmworkers at Risk: The Growing Dangers of Pesticides and Heat."

Haverford College Haverford, PA | 2016-2018

Mellon Postdoctoral Fellow and Visiting AP of Environmental Studies

- Developed and ran original courses on politics and science of sustainable agriculture, the climate crisis, and related issues
- Organized "Beyond the Grassroots," a 1-day symposium bringing together agroecology researchers, organizers, and farmer-activists

University of Lisbon Lisbon, Portugal | January-July 2016

Postdoctoral Research Fellow with EU project "Bottom-up Climate Adaptation Strategies Towards a Sustainable Europe"

- Designed, co-organized, and taught an international course on research design for research professionals, graduate students, and grassroots activists
- Facilitated visioning and strategy sessions for interdisciplinary research on bottom-up adaptation strategies with lab members in the Centre for Ecology, Evolution, and Environmental Change

EDUCATION

University of Illinois at Urbana-Champaign Ph.D., Crop Sciences | 2015

- Conducted foundational multidisciplinary study of permaculture as farming practice and international grassroots network
- Performed field research at 48 farms in 18 US states
- Administered an international web survey with responses from 44 countries

University of Vermont M.S., Plant and Soil Science | 2011

- Conducted participatory research in agroforestry design with Vermont farmers

Bard College B.A., Anthropology | 2001

- Conducted multi-country research on the alter-globalization movement

SELECTED PUBLICATIONS

Gutwein, S., Zaltzberg-Drezdahl, K., Toensmeier, E., & Ferguson, R. S. (2022). Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts. Soil Security, 9, 100076. https://doi.org/10.1016/j.soisec.2022.100076

Spangler, K., McCann, R. B., & Ferguson, R. S. (2021). (Re-)Defining Permaculture: Perspectives of Permaculture Teachers and Practitioners across the United States. Sustainability, 13(10), 5413. https://doi.org/10.3390/su13105413

Toensmeier, E., Ferguson, R., & Mehra, M. (2020). Perennial vegetables: A neglected resource for biodiversity, carbon sequestration, and nutrition. PLOS ONE, 15(7), e0234611. https://doi.org/10.1371/journal.pone.0234611

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Ferguson, R. S., & Lovell, S. T. (2017). Livelihoods and production diversity on U.S. permaculture farms. Agroecology and Sustainable Food Systems, 41(6), 588–613. https://doi.org/10.1080/21683565.2017.1320349

Ferguson, R. S., & Lovell, S. T. (2015). Grassroots engagement with transition to sustainability: diversity and modes of participation in the international permaculture movement. Ecology and Society, 20(4), 39. https://doi.org/10.5751/ES-08048-200439

Ferguson, R. S., & Lovell, S. T. (2013). Permaculture for agroecology: design, movement, practice, and worldview. A review. Agronomy for Sustainable Development, 34(2), 251–274. https://doi.org/10.1007/s13593-013-0181-6

For other publications see: Complete publication list. Google Scholar. ResearchGate.

Eric Giordano

Assistant Designer

Eric is a designer, musician, and avid composter. He has run several community gardens in NYC, where he built rainwater harvesting systems, ran a composting hub, and contributed design thinking for several garden projects. He received a Permaculture Design Certification from the Center for Bioregional Living, a Master Composter Certification from the NYC Compost Project, a Certificate of Horticulture from the Brooklyn Botanic Garden, and a Masters of Science in Ecological Design from the Conway School.

FOCUS AREAS

- Site Design & Planning
- Resilience Planning & Adaptive Design
- Landscape Analysis & Assessment
- Food Systems Evaluation & Design

TECHNICAL SKILLS

- Digital Rendering
- GIS Analysis + Assessment
- Document Production & Design
- Drone Surveying

SELECTED PROJECTS

Municipal Vulnerability Preparedness Projects: Soil Resilience Planning | Various Municipalities, MA

Mapping and production support to develop unique and comprehensive models that combine soil and other ecological data with social and cultural information to identify high impact locations for nature based solutions for climate resilience. Research and production for community engagement workshops and outreach events.

Deerfield Healthy Soils Project | Deerfield, MA

Mapping, research, graphics, and report production for a comprehensive guide to protect soil health in Deerfield, MA. Included recommended bylaw updates for protecting vulnerable soil resources. *2022 Sustainability + Resiliency Award from the American Planning Association - Massachusetts Chapter.*

Greenhouse Gas Environmental Impact Assessment | Massachusetts Environmental Policy Act Office

GIS analysis and development of environmental impact assessment model for greenhouse gas emissions and carbon sequestration loss from tree clearing associated with proposed expansion of a utility right of way.

Regenerative Land Use Experiment | Major Northeast Utility Company

Mapping and Production support for assessment of potential for additional carbon sequestration through innovative land and vegetation management practices on ROW lands across three states for a major utility. Contributed research of current land cover, carbon stocks, and management practices to develop high level toolkits for land management teams.

Appendix 3: *Soil Security* Journal Paper: "Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts (Gutwein et. al. 2022)

Soil Security 9 (2022) 100076

Contents lists available at ScienceDirect

Soil Security

journal homepage: www.sciencedirect.com/journal/soil-security

Estimating land cover-based soil organic carbon to support decarbonization and climate resilience planning in Massachusetts

Sebastian Gutwein [a,*], Keith Zaltzberg-Drezdahl [a], Eric Toensmeier [b], Rafter Sass Ferguson [c]

[a] Regenerative Design Group, 1 Chevalier Avenue, Greenfield, MA 01301, USA
[b] 47 Pequot Road, Southampton, MA 01073, USA
[c] Interlace Commons, 9 Pleasant St., Bristol VT 05443. USA

A R T I C L E I N F O

Keywords:
Soil carbon
Inventory
Soil health
Land cover
Climate change

A B S T R A C T

Land management and land cover change exert a strong influence on soil organic carbon (SOC) storage. As scientific, political, and business communities increase their awareness of the essential roles SOC plays in climate regulation and ecosystem functions, efforts to quantify the impacts of land use and management on SOC have increased rapidly. Existing methods of estimating SOC stocks from widely available data do not account for land cover, and are therefore of limited usefulness in understanding the impacts of past and future land use change. This project explores a method of linking land cover to SOC using data from public datasets and the scientific literature, to provide an SOC Inventory for Massachusetts, and compares the results to those derived from a common baseline approach. Our method derives average land cover SOC values by combining data from the USDA-NRCS Rapid Carbon Assessment and the National Cooperative Soil Characterization Database with values from a meta-analysis of scientific literature. These are applied to the total area of the 20 most abundant land cover classes of Massachusetts. We compare this land cover-based approach with a baseline using SOC values found in the Soil Survey Geographic Database (SSURGO), applied to each soil map unit found within Massachusetts. Our approach produced an estimated stock of 481 million metric tons of SOC, 29% and 109 million metric tons greater than the SSURGO baseline. We use these estimates to explore the use of the land cover based SOC values to project the impacts of likely land cover change by 2050.

1. Introduction

Soil organic carbon (SOC) is one of the largest terrestrial carbon pools on the planet. This soil carbon is not only a key driver of healthy soil function (Lal, 2016), but the 1,500 gigatons of carbon stored in earth's soils are a critical part of the global carbon cycle (Lal et al., 2021). Human land management and land cover change have exerted a strong influence on the rates of SOC sequestration and loss, significantly reducing total SOC stocks over the last 12,000 years (Sanderman et al., 2017). Increasing awareness of the links between SOC, ecosystem function, economic productivity, human health, and climate resilience has led to a strong interest in global scientific, political, and business communities to quantify the impacts of land use and management on SOC, and explore the potential of soil carbon management as a nature-based solution to climate change and food security challenges.

These efforts require the ability to establish accurate inventories of SOC that account for differences between major land cover classes and the strong influence of drainage class on SOC concentration (Nave et al., 2021). Many institutions and entrepreneurs are working to develop rapid field testing systems and remote sensing protocols which promise to provide more accurate SOC inventories. However, few field testing systems are ready to deploy and remote sensing approaches are limited by data availability (Thaler et al., 2019). In order to enable the timely protection of existing soil function, soil carbon resources, and assess the potential for additional draw down of excess atmospheric carbon while technologies and data are improved, our research team set out to

Abbreviations: C-CAP, Coastal Change Analysis Program; GSSURGO, Gridded Soil Survey Geographic Database; HSAP, Massachusetts Healthy Soils Action Plan; SCDB, National Cooperative Soil Characterization Database; NOAA, National Oceanic and Atmospheric Administration; NRCS, Natural Resources Conservation Service; RaCA, Rapid Carbon Assessment; SOC, Soil Organic Carbon; SSURGO, Soil Survey Geographic Database; USA, U.S., United States of America; USDA, U.S. Department of Agriculture.

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https://doi.org/10.1016/j.soisec.2022.100076
Received 6 July 2022; Received in revised form 22 September 2022; Accepted 16 October 2022
Available online 17 October 2022

prepare a state-scale SOC inventory using the using the data resources available from the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Survey in parallel with existing research on land cover and SOC available from peer-reviewed journals.

Over the course of a century, USDA-NRCS soil scientists mapped, sampled, and lab tested many thousands of soil units in each state to develop a comprehensive soil survey for the U.S. The Soil Survey Geographic Database (SSURGO) and its companion Gridded Soil Survey Geographic Database (GSSURGO) serve as the publicly accessible repository for this hard won data, including SOC values for each mapped soil unit (Soil Survey Staff, 2019). The extensive geographic coverage of this data set make it an attractive candidate for broadscale SOC estimation. However, a deep dive into the data shows that the SOC values provided use a single value from a 'reference pedon'. Given the strong effects exerted by land cover on SOC levels and depth (Suleman et al., 2020), estimates derived from these reference SSURGO SOC values are likely to be unacceptably inaccurate.

In 2010, the Soil Science Division of the NRCS initiated the Rapid Carbon Assessment (RaCA) which helps to address some of these shortcomings. The work of the RaCA involved collecting 144,833 samples from the upper 1 meter of 32,084 soil profiles at 6,017 randomly selected locations with a variety of land covers and testing for both organic and inorganic carbon (Soil Survey Staff, 2013). The RaCA was designed to provide statistically reliable quantitative estimates of amounts of carbon stocks in soils under various land covers and "a scientifically and statistically defensible inventory of soil carbon stocks for the U.S.". The RaCA therefore provides much more solid footing for providing national-scale SOC stock estimates, however, the land cover classes selected for sampling did not include common land covers found around more developed areas such as turf, lawn, and impervious surfaces. Therefore, in more heavily developed regions, these data are still insufficient to provide a comprehensive inventory.

In 2019, the Massachusetts Executive Office of Energy and Environmental Affairs funded our team to study state SOC stocks as part of a larger effort to develop a Healthy Soils Action Plan. The objectives of this study were to provide a statewide inventory of soil organic carbon stocks for each of the major land cover and drainage classes in Massachusetts and compare this to the SSURGO SOC baseline in order to inform long term climate change actions, land conservation efforts, and enhance farm viability.

Because Massachusetts is a heavily forested state with significant developed areas and limited agriculture, we hypothesized that simply applying the SOC values from the SSURGO database would underestimate existing stocks and suppress projected SOC losses from future land conversion and development.

2. Methods

We began by examining the relationship between SOC, land cover, and drainage class in two soil databases. After corroborating the expected correlation between land cover classes and SOC values, we calculated averages for each land cover included in these datasets. We then conducted a meta-analysis of published literature on SOC concentrations in land covers not found in those data sets including estuarine wetlands, turf, and impervious land covers. These values were used to complete the Average Land Cover SOC Value Table (Table 1) for each of the major land cover classes found in Massachusetts. Each of these average values were then applied to the total area of each composite land cover type derived from a reclassification of the Massachusetts 2016 Land Cover/Land Use map layer from MassGIS. Finally, we compared the SSURGO-based estimates to the Land Cover SOC Average estimates and found a significant difference.

In order to provide soil organic carbon estimates for each of the 20 major land cover classes in Massachusetts (2016 High Resolution Land Cover plus the HSAP forest class) our research team developed land

Table 1
The average soil organic carbon (SOC) values in metric tons per hectare for the 20 most abundant land cover classes in Massachusetts, with the land cover classification code from National Oceanic and Atmospheric Administration's Coastal Change Analysis Program (C-CAP) shown in parentheses, and the source of the SOC value. The last column in this table describes which of the two methods and data sets were used to assign the average SOC value.

2016 High Resolution Land Cover Class	Average Soil Organic Carbon MT ha 1m depth	Source of SOC Value
Impervious (2)	54	Meta-analysis/ SSURGO
Developed or Open Space (5)	99	Meta-analysis/ SSURGO
Cultivated Crops (6)	81	RaCA/SCDB
Pasture or Hay (7)	126	RaCA/SCDB
Grassland or Herbaceous (8)	113	RaCA/SCDB
Deciduous Trees- non forest (9)	54	Meta-analysis/ SSURGO
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Estuarine Forested Wetland (16)	398	Meta-analysis/ SSURGO
Estuarine Scrub/Shrub Wetland (17)	398	Meta-analysis/ SSURGO
Estuarine Emergent Wetland (18)	398	Meta-analysis/ SSURGO
Unconsolidated Shore (19)	54	Meta-analysis/ SSURGO
Barren Land (20)	54	Meta-analysis/ SSURGO
Open Water (21)	54	Meta-analysis/ SSURGO
Palustrine Aquatic Bed (22)	54	Meta-analysis/ SSURGO
Estuarine Aquatic Bed (23)	54	Meta-analysis/ SSURGO

cover SOC averages sourced from two processes. The first process extracted relevant points from two NRCS datasets using QGIS and R to determine weighted averages of SOC by land cover and drainage class (QGIS Development Team, 2020; R Core Team, 2020). The SOC values calculated through this process were for Cropland, Pasture, Forest, Palustrine Wetland, and Grassland land covers, which together comprised 89% of the total area . For all other land cover classes, soil organic carbon estimates were derived from a meta-analysis of peer-reviewed research describing SOC values by land cover type, and, where necessary, these numbers were combined with SSURGO SOC averages for those areas.

Below is a detailed summary of the process and inputs used for each method.

2.1. Baseline SOC values using SSURGO data

In order to create a basis for comparison of the impact of considering land cover in estimating SOC stocks, we calculated a baseline estimate of SOC stocks with a widely used approach using SSURGO reference values. We calculated the total stocks by assigning the standard SSURGO SOC values to each of the map units contained in the statewide soil map. Specifically, the SSURGO SOC values for 0cm-100cm depth fields found in valu1 table of the GSSURGO database were summed for all soil polygons within the state boundary. For urban areas that did not have SSURGO SOC values we used the SOC values from NRCS's more generalized Carbonscapes STATSGO2 data (Soil Survey Staff, 2014) . Areas defined as water in the SSURGO dataset were set to a value of zero SOC.

2.2. Land cover based SOC values

In order to calculate a statewide estimate based on land cover associated SOC, we used values found in the NRCS databases supplemented with values from a literature review and the SSURGO SOC valu1 table.

2.2.1. Estimating cropland, pasture, forest, wetlands, and grasslands | RaCA/SCDB

Next, our team turned to the National Cooperative Soil Characterization Database (SCDB) (National Cooperative Soil Survey, 2020) and the Rapid Carbon Assessment (Soil Survey Staff, 2013) datasets seeking sample descriptions that included drainage class, land cover or vegetation classifications, and laboratory-assessed SOC values for 0-100 cm soil profiles. With QGIS we created a buffer of the Massachusetts 25k USA state boundary (MassGIS, 1991) and used the buffer to extract all the sample points from each of the datasets located within 161 km (100 miles) of the Massachusetts, USA border.

The SCDB documents the soil classification and analysis work conducted by the Soil Survey of the NRCS over the last 60 years. This database contains 1,163 points within 161 km of Massachusetts, however, after filtering for the presence of land cover descriptions and SOC values for the top 100 cm of soil, only 48 complete points remained.

Samples in the RaCA were collected and tested by the USDA-NRCS Soil Science Division between 2010 and 2015 to support soil carbon inventory efforts. Our queries to this dataset yielded a total of 167 within 161 km of Massachusetts. Thirteen points were discarded due to missing data, leaving in 154 valid points.

These 202 complete entries from the filtered SCDB and RaCA data sets were then used as a composite for our investigation into the relationship between soil organic carbon concentrations, drainage class, and major land cover classes in Massachusetts.

2.2.2. Estimating SOC for remaining major land covers classes | meta-analysis/SSURGO

Where land cover specific SOC data was not available in the RaCA and SDBC, soil organic carbon was estimated using averages of values derived from meta-analysis of peer reviewed literature on soil organic carbon stocks found in different land cover classes, and where appropriate GIS generated SSURGO/STATSGO SOC averages for that land cover.

2.2.2.1. Sources used for meta-analysis. To determine SOC values for impervious surfaces we used the following papers: "Depleted soil carbon and nitrogen pools beneath impervious surfaces" (Raciti et al., 2012), "Carbon stored in human settlements: the conterminous United States." (Churkina et al., 2010), and “Carbon stocks in urban forest remnants: Atlanta and Baltimore as case studies.” (Yesilonis and Pouyat, 2012).

To determine SOC values for wetlands we used the following papers: “Carbon Storage in US Wetlands” (Nahlik and Fennessy, 2016), “Peatlands and Climate Change” (IUCN, 2016), “Estimation of Carbon Storage in Coastal Wetlands and Comparison of Different Management Schemes in South Korea” (Byun et al., 2019) “The Drawdown Review: Climate Solutions for a New Decade” (Foley et al., 2020).

To determine SOC values for turf we used the following papers: "Quantifying carbon sequestration of various green roof and ornamental landscape systems." (Whittinghill et al., 2014), "Multi-scale heterogeneity in vegetation and soil carbon in exurban residential land of southeastern Michigan, USA." (Currie et al., 2016), “Biogeochemical and Socioeconomic Drivers of Above- and below-Ground Carbon Stocks in Urban Residential Yards of a Small City.” (Contosta et al., 2020), “Carbon Sequestration in Turfed Landscapes: A Review.” (Guertal, 2012).

The majority of these studies were from the Northeast US, however some were from comparable global temperate climate regions.

The SOC characteristics of certain land covers including non-forest trees, unconsolidated shores, barren lands, open waters, and aquatic beds were poorly described in the literature. In those cases we used the very conservative value of 22 tons/ac that was estimated for impervious surfaces. It is likely that this resulted in an underestimation of SOC for many of these land covers.

3. Results

When we assigned the SSURGO SOC values for a 0-100cm profile to each of the map unit polygons contained in the statewide soil map of Massachusetts, we found a total estimated SOC stock of 370.7 million metric tons.

Before we could provide a statewide land cover based SOC estimate, we first had to plot the data of the 202 points from the RaCA and SCDB data sets to understand what, if any, trends could be found between land cover, drainage class, and soil organic carbon concentrations.

We plotted RaCA and SCDB together to confirm congruence between the two data sources (Fig. 1). Visual inspection of plots showed that 48 observations from SCDB did not extend the range of values found within the observations drawn from RaCA, suggesting that two data sources are compatible and can be combined and analyzed jointly.

Drainage class is known to be a significant predictor of SOC stocks (Nave et al., 2021). While the RaCA data does not record an associated drainage class for the sample points, we were able to assign the drainage class values from the dominant component of the SSURGO soil polygons dataset using the geographic location of the unobscured RaCA sample points obtained from the NRCS staff.

Once all points were classified by drainage class, the very poorly draining soils showed by far the highest concentration of SOC. This made the relationship between land cover in the other drainage classes harder to see (Fig. 2).

Once points of the Very Poorly Drained Drainage Class were removed, a clear trend emerged when SOC concentration values were plotted by land cover. We looked for separation by comparing bootstrap means and 95% confidence intervals (Fig. 3).

Furthermore, the trends we saw in land cover alone persisted in most of the drainage classes when filtered by land cover and drainage class (Fig. 4).

With R Software for Statistical Computing, we used the geometric

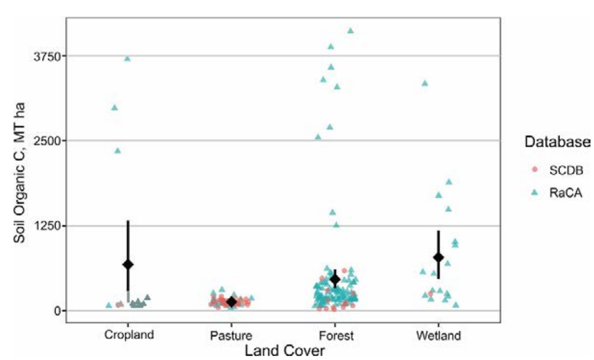

Fig. 1. Soil organic carbon by land cover for Massachusetts region, drawn from Rapid Carbon Assessment (RaCA) and National Cooperative Soil Characterization Database (SCDB). Figure shows metric tonnes of soil organic carbon per hectare to 1 meter depth, for 154 observations from RaCA and 48 observations from SCDB, drawn from within 161 km (100 miles) of the Massachusetts border. RaCA points are plotted as blue triangles and SCDB as red circles. Black diamonds and lines represent bootstrap geometric means and 95% confidence intervals based on 1000 iteration bootstrap runs.

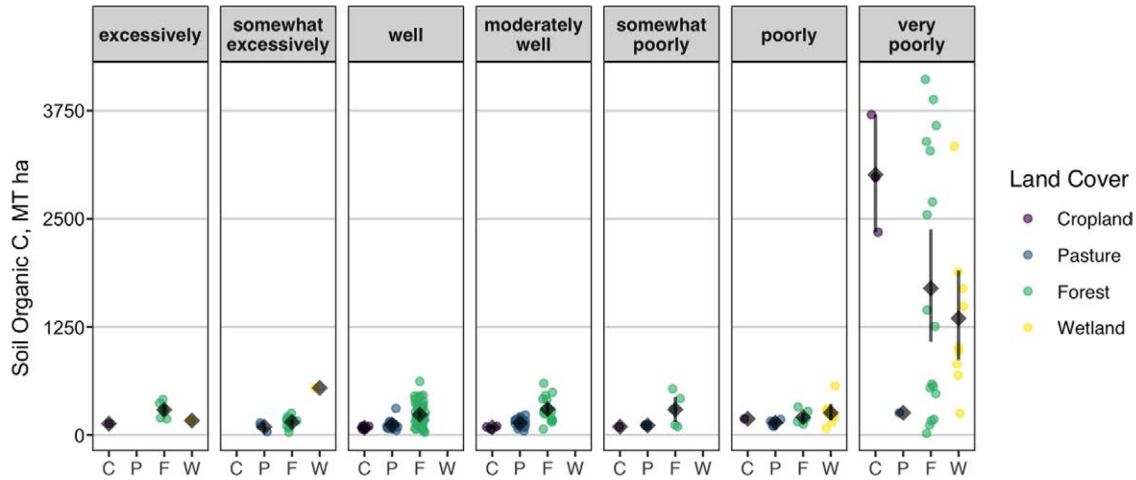

Fig. 2. Soil organic carbon by land cover and drainage class for Massachusetts region, drawn from Rapid Carbon Assessment (RaCA) and National Cooperative Soil Characterization Database (SCDB). Figure shows metric tonnes of soil organic carbon per hectare to 1 meter depth, for 154 observations from RaCA and 48 observations from SCDB, drawn from within 161 km (100 miles) of the Massachusetts border. Points are plotted by land cover within drainage class. Cropland points (C) appear in purple, pasture (P) in blue, forest (F) in green, and wetland (W) in yellow. Black diamonds and lines represent bootstrap geometric means and 95% confidence intervals based on 1000 iteration bootstrap runs.

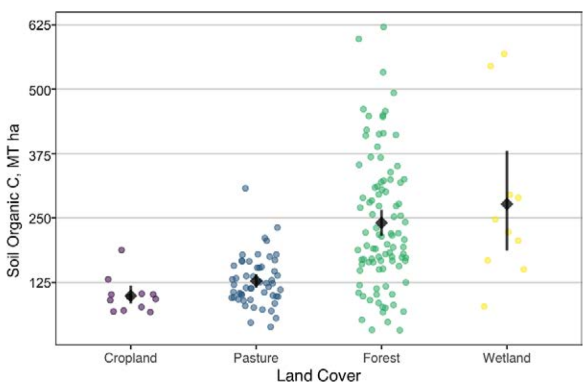

Fig. 3. Soil organic carbon by land cover for Massachusetts region with very poorly drained soils removed. Observations are drawn from Rapid Carbon Assessment (RaCA) and National Cooperative Soil Characterization Database (SCDB). Figure shows metric tonnes of soil organic carbon per hectare to 1 meter depth, for 128 observations from RaCA and 44 observations from SCDB, drawn from within 161 km (100 miles) of the Massachusetts border. Cropland points appear in purple, pasture in blue, forest in green, and wetland in yellow.

mean of the land cover and drainage class to assign an SOC value for each land cover drainage class combination. The RaCA data set combined pasture and grassland. However, when we cross walked the data to the Massachusetts High Resolution Land Cover classification, we kept pasture and grassland separate largely because grasslands tend to be located on soils with dryer drainage classes and have lower statewide SOC averages.

Taking the hectares those areas represented we calculated a statewide weighted average for each of the following land covers;

- Cropland = 80.8 metric tons per hectare
- Pasture = 126 metric tons per hectare
- Forest = 214.2 metric tons per hectare
- Palustrine Wetland = 825.3 metric tons per hectare

Additionally, we used the same data sets and process to calculate the SOC average value for grasslands.

- Grassland = 112.9 metric tons per hectare

For the remaining C-CAP land cover SOC values we relied on the values derived from meta-analysis of peer reviewed literature on soil organic carbon stocks found in different land cover classes, and where appropriate GIS generated SSURGO/STATSGO SOC averages for that land cover. The average values used for all the C-CAP classes in Massachusetts are shown in Table 1.

By applying these average values to the area of each of these land covers, we calculated the total existing stocks of SOC for all of Massachusetts to be 480.9 million metric tons. This estimate is 109 million tons greater than that of SSURGO the estimate, a difference equivalent to 1.765 billion tons of carbon dioxide.

For the purposes of the Massachusetts Healthy Soils Action Plan, we grouped the C-CAP classes into five composite land cover classes. These composites consist of Wetland (C-CAP 13, 14, 15, 16, 17, 18), Forest (C-CAP 11, 12), Agriculture (C-CAP Values 6, 7), Turf (C-CAP 5), and Impervious (C-CAP 2).

Fig. 5 shows the SOC density in these composite land cover classes and Fig. 6 shows the total stock of the SOC in the composite land cover classes.

4. Discussion

There are many new and ongoing studies seeking to provide better methods and tools for estimating or measuring SOC stocks and the effects of management practices. Relying on existing data can serve as a stop gap while methods and tools improve. This study uses land cover based SOC averages from a variety of sources to enable the estimation of total stocks. We suspect that the average values derived from the meta-analysis or the conservative values assigned where no data was found, especially for non-forest trees and aquatic beds, are likely to be low. Additional investigations focused on testing the SOC value of soils in these land cover classes as well as for impervious areas and developed open spaces would improve the accuracy of future estimates.

The work of this study generated coarse average SOC values for the dominant land covers of Massachusetts and may not be applicable at a finer geographic scale or for different regions. To achieve greater accuracy and make them applicable at finer scales or other regions, two changes to our methods should be explored. First, in this investigation, we used soil points within 160 km of the Massachusetts border, however, a more accurate average would likely be achieved by clumping the analysis of the RaCA data points into geology based areas such as the NRCS's Major Land Resource Areas. This approach would do a better job

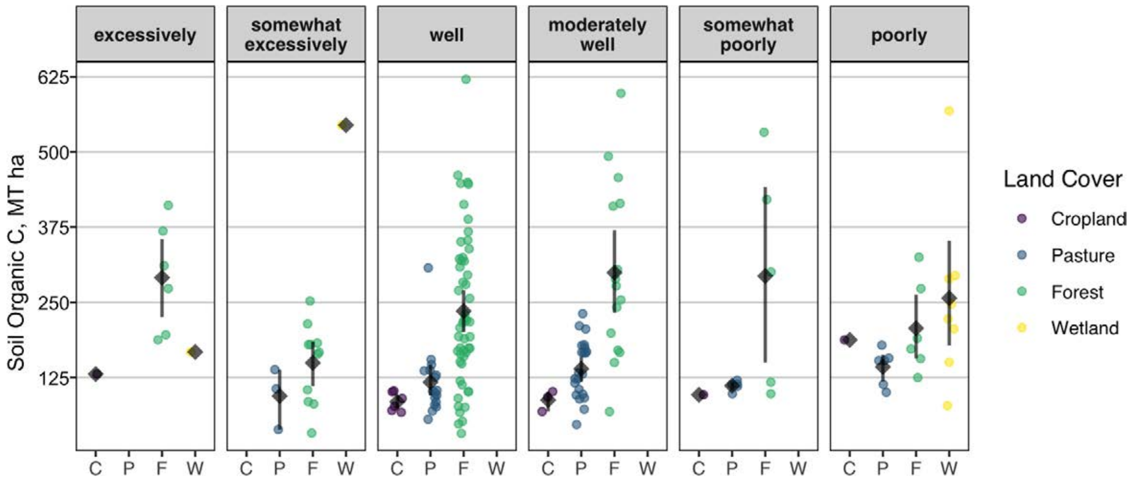

Fig. 4. Soil organic carbon by land cover and drainage class for Massachusetts region with very poorly drained soils removed. Figure shows metric tonnes of soil organic carbon per hectare to 1 meter depth, for 128 observations from RaCA and 44 observations from SCDB, drawn from within 161 km (100 miles) of the Massachusetts border. Points are plotted by land cover within drainage class. Cropland points (C) appear in purple, pasture (P) in blue, forest (F) in green, and wetland (W) in yellow. Black diamonds and lines represent bootstrap geometric means and 95% confidence intervals based on 1000 iteration bootstrap runs.

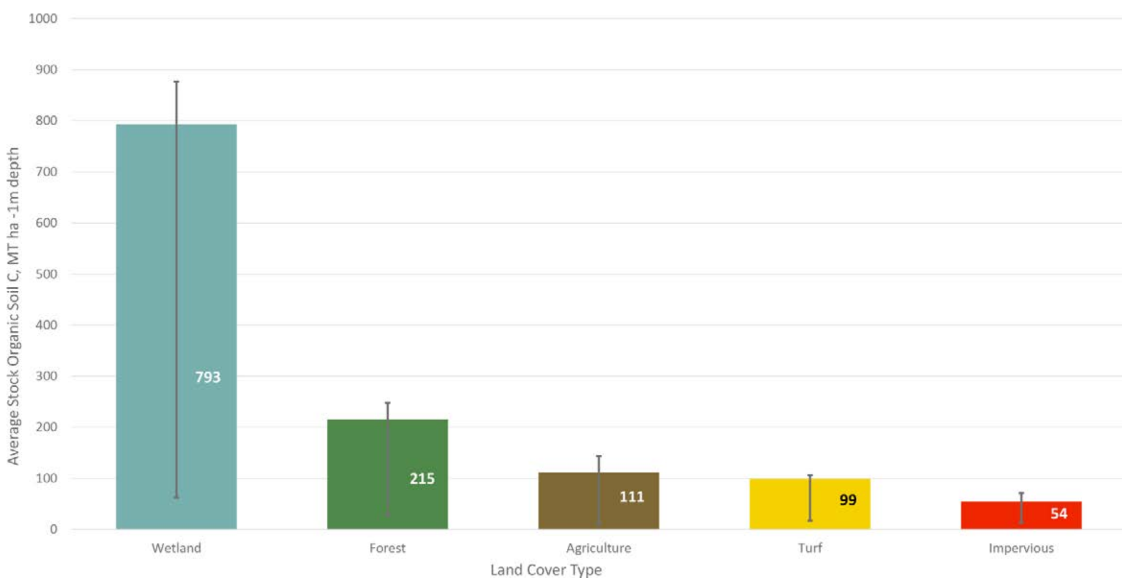

Fig. 5. The soil organic carbon density among the major composite land cover classes of Massachusetts varies dramatically. The unique soil chemistry of wetlands and powerful sequestration capacity of forests make these two land cover classes the leading stockpiles of SOC in Massachusetts. The land cover classes are the ones used for the Massachusetts Healthy Soils Action Plan. Columns indicate mean metric tonnes of soil organic carbon to one meter depth and whiskers indicate range of values.

of accounting for regions with dramatic variability in inherent SOC holding capacity such as between the very sandy Cape Cod region and the rest of Massachusetts. A second improvement would involve a change in how SOC values are assigned to land covers. Rather than simply applying a single SOC value to each land cover class, the pedon SOC values in the SCDB and SSURGO databases could be adjusted to account for the effects of the representative pedon land cover on SOC values and the effects of current land covers. For example, if the typical pedon for a soil type was based on a pasture land cover and the current land cover were forest, we would adjust the SSURGO SOC value upward to account for the expected higher SOC value. If the current land cover were cultivated, the SOC values would then be adjusted downward. Determining the amount of this land cover adjustment could be done by percent difference between land covers based on the Average Land Cover-SOC Values Table. We've experimented with this at the municipal level, and a comparison to lab results shows promising trends.

We suspect that our process could also be simplified by calculating SOC land cover averages for cropland, pasture, forest, wetlands, and grasslands using only the RaCA data points rather than both RaCA and SCDB points. The SCDB resulted in very few points and required significant processing effort. By focusing on the RaCA data points the processing effort would be reduced significantly without a large effect on the results.

While imperfect, these methods allow researchers and policymakers to rapidly establish a baseline for soil organic carbon stocks across wide regions. As in the case of Massachusetts, this baseline can then be used to inform long term efforts for climate change mitigation, land conservation, and decarbonization.

The Massachusetts Healthy Soils Bill, signed into law in January 2021, relies on these estimates to support and identify priorities for funding of actions to promote better soil management practices across land cover classes. At the municipal level or regional level,

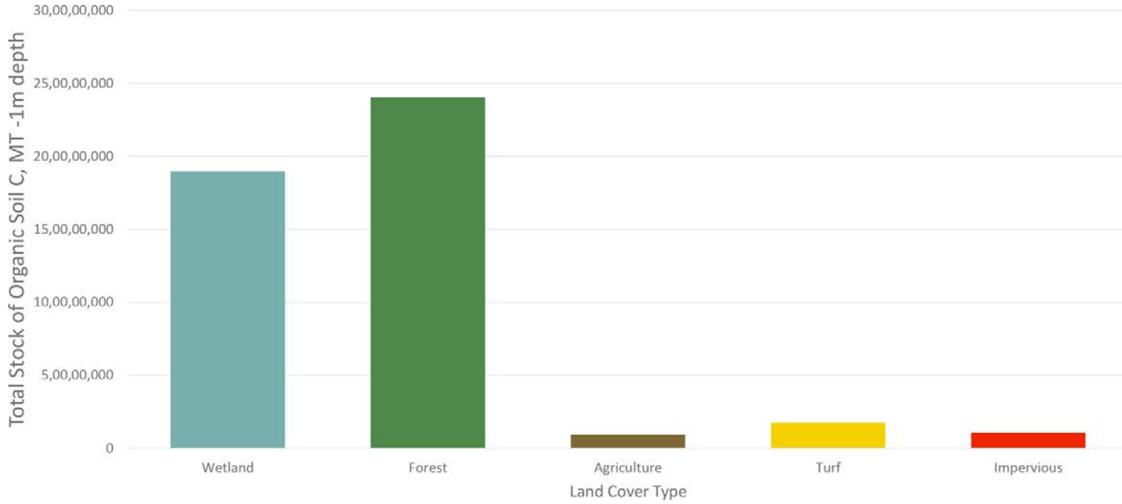

Fig. 6. This figure illustrates where the total soil organic carbon (SOC) stocks are distributed among major composite land cover classes of Massachusetts. Land cover specific estimates were calculated by multiplying the average SOC value (metric tons) for each of the composite land cover classes by the total hectares found within Massachusetts as determined by the MassGIS 2016 Land Cover/Land Use Data Layer. The land cover classes are the ones used for the Massachusetts Healthy Soils Action Plan. Y axis values are metric tonnes of soil organic carbon per hectare to 1 meter depth.

understanding which soils are the most carbon rich can help create overlay districts or other mechanisms to direct development away from rich soils, and integrate the SOC impacts of land conversion into design and planning processes.

Using these same land cover-based SOC values, it is possible to project how planned land cover changes might affect soil organic carbon fluxes over time. For instance, according to a recent study on land consumption from Harvard Forest, the majority of future development in Massachusetts is likely to occur on forested lands (Thompson et al., 2020). The average land cover SOC values developed for this study show that soils under turf hold 54% less soil organic carbon than when forested, and impervious soils 74% less. A projection of recent trends in land cover change prepared for the New England Landscape Futures project predicts that more than 116,000 hectares of forest land will be converted to residential and other developments by 2050. Using the differential SOC values from this study, this land cover change will emit over 1.4 million metric tons of CO2e per year. This could be mitigated by implementing policies to shift new development onto areas with turf and impervious land cover instead of forest.

Inversely, by implementing a variety of soil-smart management practices and climate-informed planning approaches, soil-based contributions to climate change mitigation can be increased significantly. For example, the forth-coming Massachusetts Healthy Soils Action Plan shows that by employing the best land management practices, enhanced annual natural sequestration could remove an additional 473,000 tons of CO2 from the atmosphere annually.

5. Conclusions

The analysis of soil sample data within 161 km of Massachusetts from both the Rapid Carbon Assessment and the National Cooperative Soil Characterization Database confirmed that land cover, when isolated by drainage class, plays a large role in SOC levels and showed a significantly higher SOC baseline when compared to a SSURGO-derived estimate.

This inventory, and those like it, can help researchers, policymakers, planners, and those involved in voluntary carbon markets to easily see the relative significance of soil carbon pools within and between various land cover classes and establish priorities for conservation, regeneration, and future research.

CRediT authorship contribution statement

Sebastian Gutwein: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Keith Zaltzberg-Drezdahl:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Eric Toensmeier:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **Rafter Sass Ferguson:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

Funding for this work was provided by the Massachusetts Executive Office of Energy and Environmental Affairs as a part of the Massachusetts Healthy Soils Action Plan. We would like to thank Maggie Payne, from the Massachusetts Soil Survey and Skye Wills with the National Rapid Carbon Assessment team (NRCS, LIncoln NE) who provided invaluable guidance and support on the methods of this investigation. Caro Roszell of American Farmland Trust, Marty Dagoberto of the Northeast Organic Farmers Association, and Jim Newman of Linnean Solutions provided excellent advice on the structure of this article and were our partners in the larger Healthy Soils Action Plan process.

Appendix

Processing details for SSURGO SOC baseline

The majority of the raw SOC data we used came from the NRCS SSURGO valu1 table SOC_0-100 cm SOC values. For urban areas, mines, and water, which lack SSURGO data, we used the values from the USDA carbonscapes STATSGO2 SOC 0-100 cm. The Carbonscapes data was downloaded as a 100 × 100 m raster and as a personal geodatabase that we extracted the table from, joined it to the layer STATSgdb, and created a new raster file with the values from STATSGO2 SOC 0-100 cm. A new attribute was created in the SSURGO valu1 table that was the average value in each soil polygon from the STATSGO2 SOC 0-100 cm raster. We then created another attribute that used the values from STATSGO2 if they were missing in SSURGO.

GIS data layers and processing notes

The foundation of our analyses was existing statewide soil carbon and land cover data sets. Below is a description of which data sets were used and how we processed them to achieve a more fine-tuned map of SOC stocks across the state.

Land cover

The land cover data used came from the Massachusetts 2016 High Resolution 1-meter Land Cover Data obtained through the NOAA data access viewer downloaded as multiple raster files (MassGIS, 2019).

A preprocessing phase merged the 2016 land cover rasters into one virtual raster (.vrt) using GDAL Build Virtual Raster in QGIS. The resulting raster was clipped to the Massachusetts 25k state boundary using the GDAL Clip Raster by Mask Layer in QGIS. The layer was then Resampled to 3m resolution using the GDAL warp with “nearest neighbor”. Finally, it was saved as a packbits compressed unsigned 8bit raster tif file with 255 as nodata projected to EPSG 26986 NAD83 / Massachusetts Mainland Meters.

In order to isolate “Forests” from “Trees” the 2016 LC raster was reclassified to include only tree values (9,10,11,13,16). The resulting raster was then vectorized and any polygons less than .4 hectare in size were removed. We then processed an internal buffer of -18m to remove any treed areas narrower than 36m and buffered the resulting layer by 18m to return remnants from the negative buffer back to their original size. We again removed any polygons less than .4 hectare in size and buffered the remaining polygons by an additional 3m (the pixel size) to capture all of the original pixels. Finally, we reclassed the LC to only include (9,10,11), and clipped the original polygons by the +3m three polygons, and rasterized the resulting layer. The result was a “Forest not Trees” layer that also did not include forested wetlands.

To combine the “Forest not Trees” layer with the Massachusetts 2016 High Resolution Land Cover we used the SAGA GIS Patching algorithm in QGIS to replace the tree areas (values 9,10) with Mixed Forest (value 11). Finally, we saved as a packbits compressed unsigned 8-bit raster tif file with 255 as nodata projected to EPSG 26986 NAD83 / Massachusetts Mainland Meters.

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Appendix 4: Letters of Support

Dr. Jennifer Watts
149 Woods Hole Road,
Falmouth, MA 02540

Tom Anderson
100 Cambridge Street
9th Floor
Boston, MA 02114

Dear Mr. Anderson,

I, Dr. Jennifer Watts (Woodwell Climate Research Center), would like to express our support for Regenerative Design Group's (RDG) proposal to develop new **soil organic carbon GIS layers** for the entire state of Massachusetts as a response to the Challenge Grants Implementing the Commonwealth's Healthy Soils Action Plan (HSAP).

The proposed soil organic carbon (SOC) GIS layers will be invaluable for municipalities, landowners, and other stakeholders, to identify key locations for protecting important high-performing soil resources and implementing high-impact projects. Without a GIS layer that maps and quantifies this important metric of current and potential soil performance, it is likely that time, energy, and resources would be wasted on ineffective efforts.

RDG has done extensive work to understand and map soil function and soil organic carbon through their involvement as lead-authors of the Massachusetts Healthy Soils Action Plan and in directing the soil mapping components of several Municipal Vulnerability Preparedness grant projects. By synthesizing existing soil and land use data, their approach to mapping soil organic carbon provides a nuanced prediction of current and potential SOC levels. Their proposed methodology demonstrates a thoughtful and innovative approach that addresses gaps in existing data.

I wholeheartedly endorse Regenerative Design Group's application for the Healthy Soils Challenge Grant and believe that this project will significantly contribute to the objectives set forth in the HSAP. If further information or clarification is required, please do not hesitate to contact me.

Thank you for considering this letter of support, and I look forward to witnessing the positive impact that these projects will undoubtedly have on the soil health of Massachusetts.

Sincerely,

Dr. Jennifer D. Watts

United States Department of Agriculture

Natural Resources Conservation Service
Massachusetts State Office, 451 West Street, Amherst, MA 01002
413-253-4350 | fax 855-596-7666 | www.ma.nrcs.usda.gov

January 26, 2024

To Whom It May Concern:

Re: Regenerative Design Group Soil Organic Mapping Healthy Soil Challenge Grant Proposal

I am writing to acknowledge that as the NRCS State Soil Scientist for Massachusetts, I will serve in an advisory capacity to the Soil Organic Mapping Project proposed by the Regenerative Design Group to provide guidance on the incorporation of the Soil Survey Geographic Database (SSURGO) data into a statewide GIS layer that would represent current and potential soil organic carbon levels.

Sincerely,

MARGOT PAYNE Digitally signed by MARGOT PAYNE
Date: 2024.01.26 11:56:34 -05'00'

Maggie Payne
State Soil Scientist, NRCS Massachusetts and Vermont

Tom Anderson
100 Cambridge Street
9th Floor
Boston, MA 02114

Dear Mr. Anderson,

The Trustees would like to express our support for Regenerative Design Group's (RDG) proposal to develop new **soil organic carbon GIS layers** for the entire state of Massachusetts as a response to the Challenge Grants Implementing the Commonwealth's Healthy Soils Action Plan (HSAP).

The proposed soil organic carbon (SOC) GIS layers will be invaluable for conservation organizations like ours as well as municipalities, individual landowners, and other stakeholders to identify key locations for protecting important high-performing soil resources and implementing high-impact practices. Without a GIS layer that maps and quantifies this important metric of current and potential soil performance, it makes calculating this significant indicator challenging and inconsistent.

RDG has done extensive work to understand and map soil function and soil organic carbon through their involvement as lead-authors of the Massachusetts Healthy Soils Action Plan and in directing the soil mapping components of several Municipal Vulnerability Preparedness grant projects. By synthesizing existing soil and land use data, their approach to mapping soil organic carbon provides a nuanced prediction of current and potential SOC levels. Their proposed methodology demonstrates a thoughtful and innovative approach that addresses gaps in existing data.

I wholeheartedly endorse Regenerative Design Group's application for the Healthy Soils Challenge Grant and believe that this project will significantly contribute to the objectives set forth in the HSAP. If further information or clarification is required, please do not hesitate to contact me.

Thank you for considering this letter of support, and I look forward to the positive impact that these projects will undoubtedly have on the soil health of Massachusetts.

Sincerely,

Jennifer Core, Director of Agriculture
The Trustees

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Revised: February 1, 2024