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Soil carbon storage and sequestration in Vermont Agriculture

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Alissa White, Heather Darby & Donald Ross. Research Brief, April 2022.
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Introduction

In 2021, The State of Soil Health (SOSH) project measured indicators of soil health on 221 farm fields across the state of Vermont through a collaborative effort among many organizations. Soil carbon stocks to 30 cm depth were assessed on 191 of those fields. In this brief we share a summary of this new soil carbon stock data alongside data from a national assessment of soil carbon stocks performed by the NRCS from 2010 and highlight its relevance to current policy conversations within the state of Vermont.

Key Ideas

- The protection of existing soil carbon stocks and support for increased carbon sequestration align with both environmental and agricultural goals.
- A collaborative effort to collect and share soil health information in 2021 provides needed state scale data on soil health and soil carbon in Vermont's agricultural landscapes.
- Northeastern soils and climate are naturally conducive to high levels of soil carbon.
- When compared regionally and nationally, Vermont's agricultural soil carbon levels are high. An average of 86 MT carbon per hectare and 4.3% organic matter was observed.
- A wide range in soil health scores and soil carbon levels observed in soil samples showed both that some fields have high levels of carbon storage, and many fields had low carbon levels indicating there are opportunities to further sink more carbon.
- Long term studies in Vermont have documented agricultural soil carbon sequestration rates at between 0.39 and 6.43 MT Carbon per hectare per year. That's equivalent to a range of 1.4 to 23.6 MT CO_2 per hectare per year.
- Increases in soil carbon are possible on Vermont farms, and can complement other strategies to reduce concentrations of atmospheric greenhouse gasses.
- The permanence of soil carbon in our region is linked to agricultural economics, farmer capacity and capability. Permanence can be addressed in part through support of Extension technical assistance, policy and conservation incentive program design.
- Policy tools can help protect the high soil carbon stocks in Vermont. Incentives to maintain high levels of soil carbon for farmers, such as cost-shares or payment-for-ecosystem services programs, should be considered by policy makers.
- Additional research on common and innovative soil management strategies and their influence on soil carbon sequestration in Vermont agriculture is needed.
- Soil carbon changes are only one part of the whole farm carbon balance, and more research is needed to assess how soil carbon changes influence climate change mitigation compared to other interventions on farms in Vermont.

Carbon storage: How much carbon is in Vermont's agricultural soils?

Statewide assessments of soil carbon stocks have been conducted in Vermont using standardized and comparable methods in two recent efforts. Both efforts directly measured organic soil carbon content and bulk density, providing reliable empirical data for calculating soil carbon stock estimates. In 2010, the NRCS conducted a national assessment of soil carbon stocks called the Rapid Carbon Assessment (RaCA) with comparable measurements from every state in the US[i]. This NRCS RaCA effort evaluated carbon stocks to 5 cm, 30 cm and 100 cm depths at 53 locations in Vermont, 23 of which were in agriculture.

In 2021, the State of Soil Health (SOSH) project conducted standardized assessments of soil carbon stocks alongside evaluations of a suite of soil health indicators in farm fields across the state of Vermont. This SOSH effort evaluated carbon stocks to 30 cm depth on 191 fields in Vermont[ii], providing a more extensive dataset with which to describe agricultural soil carbon.

NRCS Rapid Carbon Assessment

The national RaCA assessment offers a window into the way climate and soil type influence soil carbon. Finely textured soils of glacial origin have a high affinity for holding carbon, and the cold temperate climate of the northeast prevents losses. Together, these **conditions contribute to our region having higher soil carbon stocks than the national average** (Figure 1).

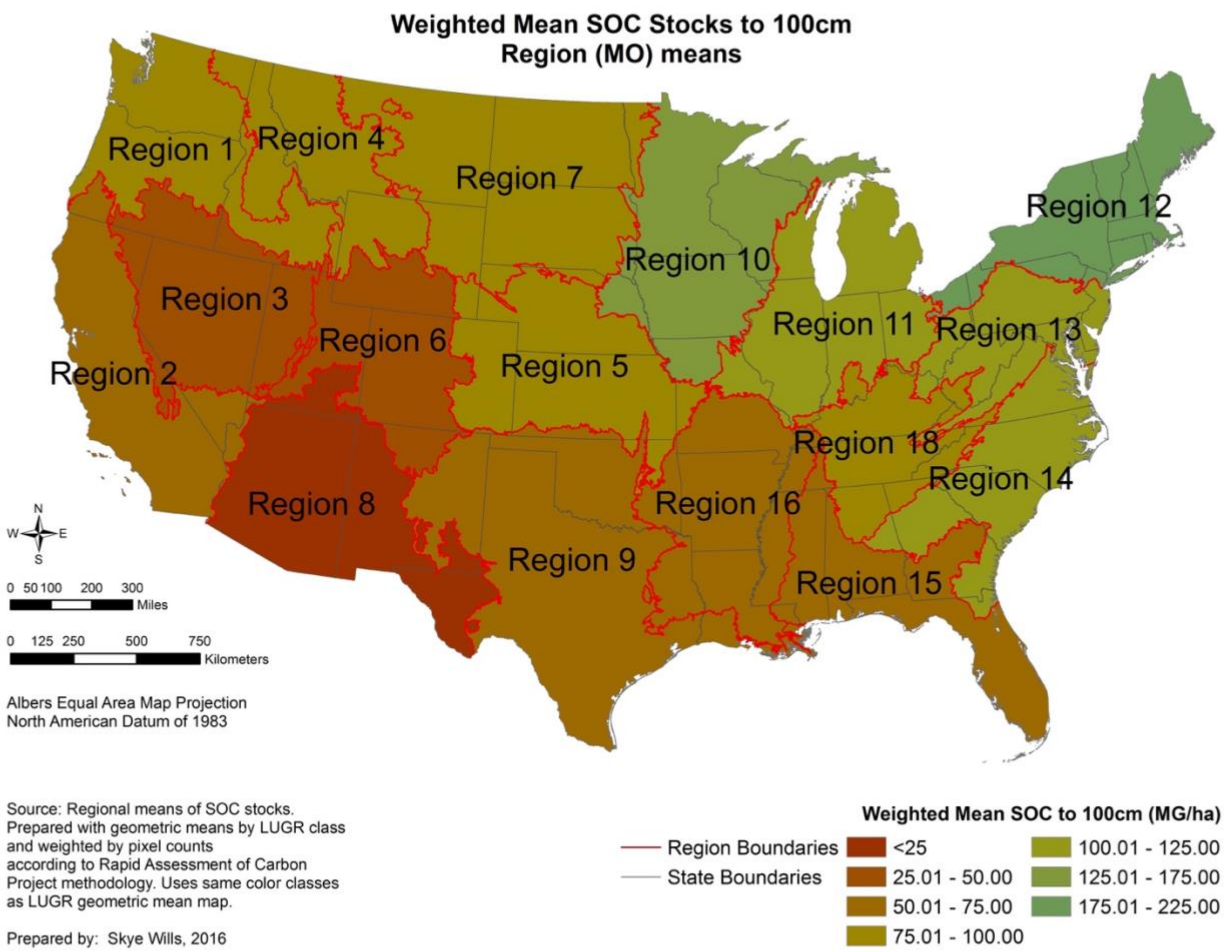

Figure 1. Average soil carbon stocks to 100 centimeter depths by region from the NRCS RaCA assessment. Northeastern soils have the greatest soil carbon stocks on average. Figure by Wills 2016 from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_052842.pdf

The RaCA assessment offers comparable data on soil carbon stocks to multiple depths across land uses, but also highlights the high degree of variability and uncertainty in wetland and forest soil carbon estimates at the state scale based on that data (Figure 2). Only three wetland soils were evaluated, but the range is extensive. Soil carbon stock data should only be compared if measured to the same depth. Sampling to 100 cm depth was not conducted for all forest soil locations for this project, likely due to large coarse soil fractions, tree roots, and depth to bedrock.

Forests and wetlands tend to have the highest soil carbon stocks, making them an important priority for soil carbon protection in Vermont. The median soil carbon stock to 30 cm depth in Vermont from this NRCS RaCA assessment was 87.4 MT C/ha in cropland and 76.7 MT C/ha in pasture and haylands. High outliers tend to skew the data distributions in this dataset, meaning that average values are higher than the median, so the median is reported here. In Vermont forests, which make up approximately 76% of land cover[iii], the median RaCA soil carbon stock to 30 cm depth was 150.7 MT C/ha (Table 1). Other recent work in Vermont found somewhat lower soil carbon stocks at 18 managed forest sites: 147 MT C/ha to an average depth of 78 cm[iv]. Nonetheless, these stocks are still much higher than found in agricultural soils. Ongoing monitoring of soil carbon in five high elevation unmanaged forest sites (range in soil carbon stocks to 100 cm depth of 178-405 MT C/ha) shows significant increases over the past two decades[v]. Keeping our forests and wetlands intact should promote continued soil carbon sequestration.

The overlap of ranges in the data here indicates that under some management and soil conditions, agricultural fields have soil carbon stocks within the expected range for forest and wetland soils (Figure 3). Prior to agriculture, these soils certainly should have had carbon stocks similar to today's forests. **Agricultural soils are an opportunity to both maintain and increase soil carbon content.**

Table 1. Soil organic carbon stocks to 5, 30 and 100 cm depths in Vermont soils from the NRCS RaCA dataset, 2010.

		Median MT Carbon per hectare		
Land cover	**Number of fields**	**5 cm depth**	**30 cm depth**	**100 cm depth**
Cropland	8	21.9	87.4	112.2
Forest	27	61.7	150.7	247.0
Pasture & Hay	15	23.5	76.7	112.2
Wetland	3	27.2	120.5	168.0

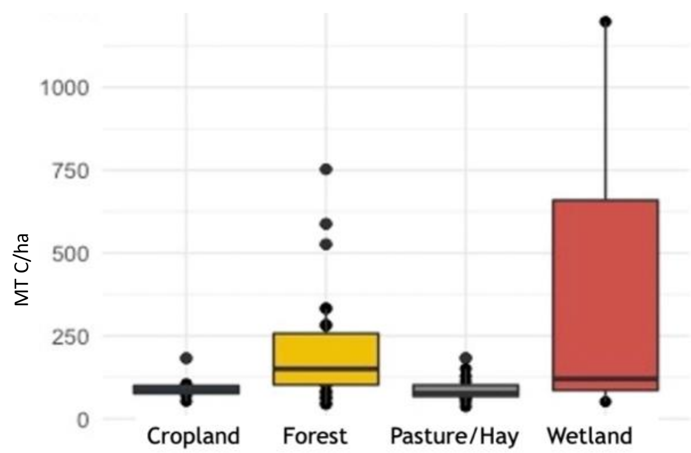

Figure 2. Boxplots of soil organic carbon stocks to 30 cm depth in Vermont soils from the 201 NRCS RaCA dataset.

Figure 3. Bulk density soil cores collected for the State of Soil Health project.

State of Soil Health in Vermont

Based on data collected by the SOSH project in 2021, average agricultural soil carbon stocks to 30 cm depth in Vermont agricultural soils are 86.1 MT C/ha across all field types. Comparatively, the average 30 cm depth soil carbon stock for all VT agricultural soils in the RaCA data is 92.2 MT C/ha. The SOSH data represents eight times as many fields across a greater diversity of Vermont cropping systems. Differences could be due to slightly different sampling approach, field methods or lab analyses. For the SOSH project, soil was collected in composite field-scale samples to 30 cm depth which were analyzed for soil organic carbon content, accompanied by three 30 cm long hammered bulk density cores in a transect across the field. RaCA methods are described in Soil Survey Staff (2016)[i].

Soil carbon stocks to 30cm depth assessed on Vermont farm fields in 2021 ranged from 31.1 MT C/ha to 170.4 MT C/ha (Table 2). We found especially wide variability among corn and hay fields (Figure 4). ANOVA analysis found that carbon stocks differed significantly by crop type ($p<.05$). Average soil carbon stocks for vegetable fields were 65.1 MT C/ha, corn fields were 84.1 MT C/ha, hay fields were 94.1 MT C/ha and pasture fields were 95.8 MT C/ha.

Table 2. Soil carbon stocks to 30 cm depth in MT carbon per hectare, collected on Vermont farms in 2021 by the State of Soil Health project.

Field Type	Number of fields	MT Carbon per hectare Min	Mean	Max
Vegetable	17	31.1	65.1	98.6
Field crops	4	75.7	107.7	148.8
Corn	112	33.4	84.1	144.0
Pasture	21	63.4	95.8	170.4
Hay	37	31.3	94.1	164.1
All fields	*191*	*31.1*	*86.1*	*170.4*

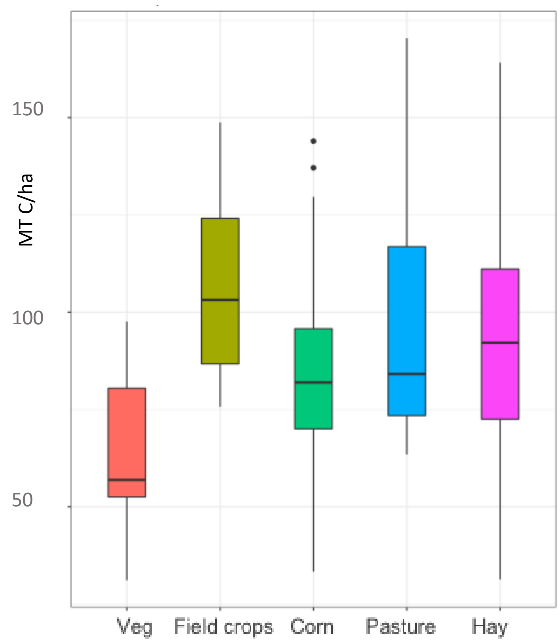

Figure 4. Soil carbon stocks in Vermont measured in 2021 by the State of Soil Health Project.

Soil organic matter: indicator of carbon sequestration

Soil carbon stocks are improved through changes in soil organic matter. Organic matter is the living or formerly living portion of the soil. It is a reservoir of organic carbon, biological activity, and nutrients; and is foundational to many ecosystem services and soil functions. This pool of organic carbon is influenced by soil texture (Figure 5) but can be improved by management strategies that limit soil disturbance and increase inputs of biological carbon such as cover crops, crop residues, manure or other forms of organic carbon.

Approximately half of soil organic matter is carbon[vi]. Increases in soil organic carbon content indicate an overall net gain in carbon that constitute carbon sequestration**.** This is carbon that used to be in the atmosphere as CO_2, was taken up by plants, decomposed, and accumulated in the soil. In this way, increases in soil organic carbon contribute to mitigating the drivers of climate change by offsetting greenhouse gas concentrations in the atmosphere.

Organic matter content is the key indicator of change in soil organic carbon most widely tracked by farmers and researchers. **Organic matter content in Vermont's agricultural soils is high when compared against national and neighboring states' numbers.** Average soil organic matter content based on the SOSH data for agricultural fields in Vermont is 4.3% (Table 3). National mean organic matter content in agriculture based on the RaCA data is 3.2%. In New York, average agricultural field organic matter content is 3.1%[vii]. **High organic matter content on Vermont farms is evidence of good soil stewardship by many farmers.**

High variability in soil organic matter content points to two important considerations. First, this data demonstrates that there are many fields that have very low soil carbon and organic matter content, which have a high potential for additional soil carbon gains through adoption of best management practices. Second, the data provides evidence of high levels of carbon content that are achievable in the Vermont farm context. This is important information to inform farmers and policy makers in charting what might be possible with an 'all-in' approach to building soil carbon. The highest organic matter content we measured on a farm in 2021 was 9.1%, and we saw evidence that every crop type and soil texture could reach 5% to 7% organic matter content, though coarse soils will be more difficult to improve.

Table 3. Soil organic matter content collected on Vermont farms in 2021 by the State of Soil Health project.

Field Type	Number of fields	Soil organic matter			
		Min	Mean	Q3	Max
Vegetable	20	1.5%	3.7%	4.9%	6.2%
Field crops	4	3.6%	5.5%	6.7%	7.3%
Corn	112	1.6%	4.1%	4.7%	7.2%
Pasture	21	3.1%	5.3%	6.2%	9.1%
Hay	38	2.3%	4.8%	5.8%	7.5%
All fields	*195*	1.5%	4.3%	5.3%	9.1%

This means that **there are gains to be made in soil carbon on every farm in Vermont if they have the means, knowledge and motivation.**

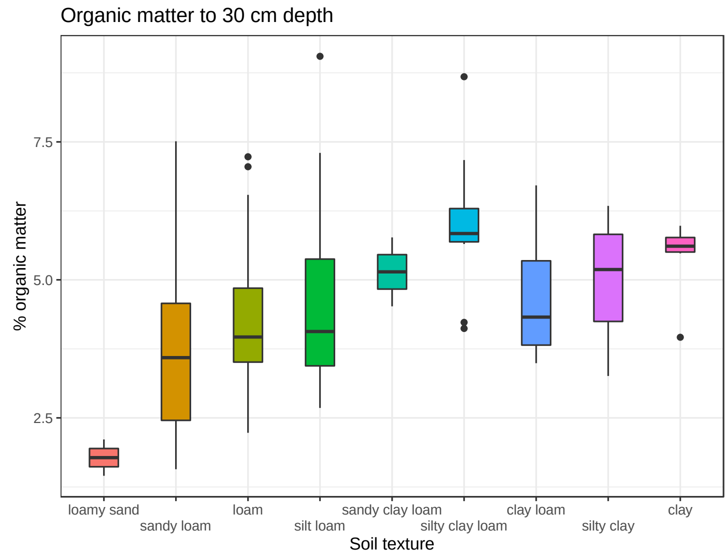

Figure 6. Organic matter content by soil texture from the State of Soil Health project in 2021.

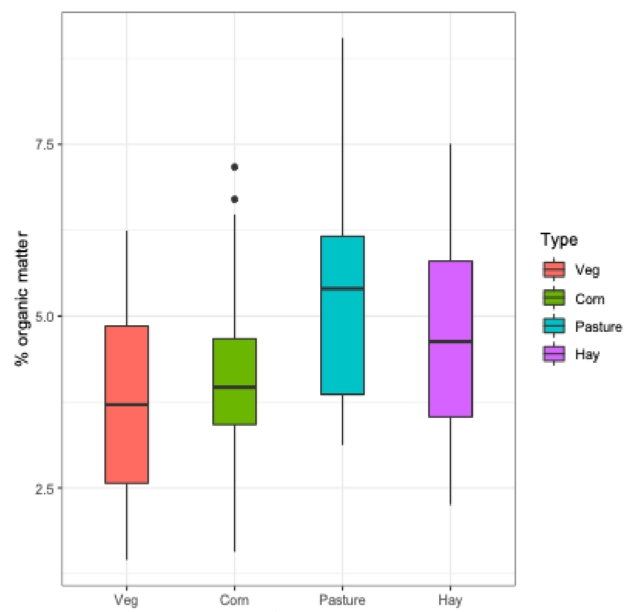

Figure 5. Organic matter content by crop type.

Additionality evidence in Vermont: Long term research plots document changes in soil carbon

Soil carbon sequestration in agricultural soils is a long-term endeavor. Changes in organic matter often take 5 to 7 years to show up in a routine soil test and can easily be lost to increases in tillage or changes in management. Evidence that recommended practices lead to additional soil carbon in this climate on Vermont soils is an important underpinning for conservation programs and policy. Two longitudinal studies in Vermont provide recent local evidence with which to temper expectations for soil carbon sequestration.

Long term replicated trial research on silage corn cropping systems at Borderview Research farm in Alburgh, Vermont documents the impact that cropping management without manure additions has on soil organic carbon.[viii] This research has been running for 11 years, and plots have tracked the way continuous corn differs from corn-hay rotations, no-till corn, winter cover cropped corn, and a no-till/cover crop corn in combination (Table 4). Plots with corn hay rotations, no-till, and combined no-till cover crop treatment performed significantly better in organic matter content when compared with continuous corn with conventional tillage. The treatment with only winter cover crop did not have significantly greater organic matter compared to continuous corn. Significantly different treatments had an additional 0.96% to 0.26% organic matter. Full details of the study are available on the UVM Northwest Crops and Soils website, https://www.uvm.edu/extension/nwcrops, and linked in the references at the end of this document.

Another recently published longitudinal study in Vermont tracked changes in organic matter among two sets of paired fields over 6 years[ix] (Table 5). In one pair of fields, the study measured relative changes in organic matter between a hay field with broadcast manure compared to a hay field with aeration before manure broadcast. The other pair compared a conventional till and broadcast manure corn field to a best management corn field with winter rye cover crop, reduced till and manure injection.

Table 4. Long term research trial of corn cropping systems at Borderview Farm documents changes in organic carbon content. Treatments with the same letter did not perform significantly different from each other. ***Bolded treatments were significantly different from continuous corn.*** *Additional annualized change in organic matter is the additional amount of organic matter in the treatment compared to the continuous corn treatment, divided by the span of the experiment (11 years).*

Corn cropping system	Organic matter % in 2021	Additional annualized change in organic matte over 11 years over continuous corn
Continuous corn	3.29% [c]	~
Corn-hay rotation, year 2	**4.25% [a]**	**0.087%** per year
Corn-hay rotation, year 7	**3.55% [b]**	**0.024%** per year
No till	**3.60% [b]**	**0.028%** per year
No till and cover crop	**3.56% [b]**	**0.025%** per year
Winter cover crop	3.28% [c]	~

Table 5. Paired field study over 6 years documented changes in organic matter on treatment and control plots. Additional annualized change in organic matter is the additional amount of organic matter in the treatment compared to the control, divided by the span of the experiment (6 years).

Treatment	Change in organic matter % from 2012-2018	Annualized change (per year rate)	Additional annualized change in organic matter over 6 years over control
Hay control	2%	0.33% per year	~
Hay with aerator	1.6%	0.26% per year	- 0.07% per year
Corn control	0.5%	0.08% per year	~
Corn BMP	0.8%	0.13% per year	0.05% per year

For both of these longitudinal studies we have calculated the difference in organic matter attributed to the treatment, and then divided it by the time period of the study, to get an annual rate of additional organic matter (Table 4 & 5). Based on this data from Vermont, **current practices that incorporate manure applications can increase organic matter annually within a range of 0.08% to 0.33%** (Table 5), though the same study found that **some manure management strategies can result in greenhouse gas emissions that offset those carbon gains in some cases**[viii]. The adoption of **recommended practices in corn fields in these studies resulted in additional 0.09% to 0.02% organic matter** content in soils when compared to continuous conventionally managed corn (Table 4 & 5). If we assume the bulk density of the soil is 1.3 g/cm^3, these studies have documented agricultural soil carbon sequestration rates between 0.39 and 6.43 MT Carbon per hectare per year in the top 30 cm of soil. That's equivalent to sequestering 1.4 and 23.6 MT CO_2 per hectare per year.

The studies we cited here are the best longitudinal data on soil carbon changes due to agricultural management that we are aware of within Vermont. Management and soils are different on every farm, and replicated long-term tracking of soil carbon is needed to expand this evidence base for other farm practices and contexts.

Policy relevance

Greater attention on soil carbon sequestration as a climate change solution has increased both optimism and scrutiny of the potential for soil carbon gains to offset atmospheric greenhouse gas emissions. In some places, the urgency of the climate crisis has prompted every tool to be leveraged in mitigating atmospheric greenhouse gas concentrations, including soil carbon sequestration, though three key concerns about uncertainty are generally raised. The first is about a lack of baseline data. The second is about uncertainty in saturation and additionality. The third is about permanence. All of these concerns are based on uncertainty in outcomes. The data shared in this brief and collected by the State of Soil Health Project addresses some of this uncertainty. If policy-makers are able to address these concerns of uncertainty, they may include the quantification of carbon sequestration in their suite of strategies to address the climate crisis, especially if they have realistic estimates of the potential impact soil carbon gains may have in meeting environmental goals, approaches to verifying them, and strategies to protect soil carbon permanence.

Baseline data

Understanding current levels of soil carbon in Vermont is essential to setting informed goals. The State of Soil Health Project has collected new statewide scale data on current levels of soil carbon on farms and associated indicators of ecosystem services which can be leveraged to inform policy and farm goals. This dataset may also be leveraged in future analyses to explain the degree to which land use history, soil texture and management influence soil carbon on Vermont farms. Our assessment identifies current levels of soil carbon that differ by crop type and are higher than the national average. However, our climate and soils are conducive to higher soil carbon levels, and our expectations should be higher too.

Saturation and Additionality

Soils are understood to have a maximum level of carbon that they can hold, and this is referred to as a saturation point. Soil organic carbon is constantly cycling and changing, and soil carbon content is a balance of carbon inputs and losses influenced by temperature, moisture and biology. Climate and soil texture strongly influence saturation potential. Soil carbon gains cannot be made indefinitely, so the potential for sequestration in soils is theoretically limited. Together, understanding current levels of soil carbon as a baseline and an estimated saturation point, or maximum, are used to estimate of the overall amount of carbon that soils can sink over time. There is no evidence that we have reached a saturation point for agricultural soils in Vermont. In fact, soil organic matter levels of over 5-7% are realistically achievable for farms, and evidence of getting to 9% exists. Carbon content of our forest soils is even higher, and innovations in agricultural management that mimic the carbon cycling in forest ecosystems have the potential to get closer to those levels of sequestration. Forests soils in Vermont vary but are more likely to be close to saturation than farm field soils and have less gains to make.

There is evidence that additional soil carbon sequestration may be achieved through the adoption of recommended practices that reduce tillage and increase organic matter inputs through residues, compost, and manures. Variability in the outcomes of adopting practices can be addressed through models that take into account soil characteristics or through direct measurement. Accounting for only the changes in agricultural soil carbon stocks does not account for other greenhouse gas emissions from soils, or other areas of farms. Farms in Vermont often manage large acreage in sugarbush, riparian buffers, and forests which also additional above and below ground sequestration potential. Livestock farms must also consider enteric and manure management emissions. Assessments at the whole farm scale have produced various conclusions about the degree to which sequestration can offset emissions in livestock-based farms-- in some cases making the farms a net sink[x], and in some cases net source of greenhouse gas emissions[xi]. **Soil carbon changes are only one part of the whole farm carbon balance, and more research is needed to assess how soil carbon changes influence climate change mitigation compared to other interventions on farms in Vermont.**

Permanence

When carbon is sequestered, there is always uncertainty that it has been sequestered permanently. This risk of loss may be greater for aboveground biomass (such as forest carbon stocks that could be lost from fire) but is also a concern on farms. In agricultural soils, major changes in farm management practices that increase disturbance or net removals of carbon may reduce soil carbon levels after they have been improved. Research with Vermont farmers indicates that these kinds of changes in management are primarily influenced by financial and knowledge limitations [vi, xii, xiii]. When Vermont farmers have the financial capacity to invest in and sustain conservation stewardship, they generally do. Policy and programs that increase farmers' financial capacity and educational outreach supports can address permanence of both existing soil carbon stocks and additional soil carbon stocks.

Co-benefits

One of the most compelling reasons for policy and programs to value and invest in protecting soil carbon storage and enhancing sequestration is that soil carbon is strongly linked to many societal and farm-scale co-benefits. Soil carbon is the foundation of soil health, which can enhance climate resilience, water quality and farm productivity. The promise of these co-benefits may balance some of the uncertainty in long term carbon sequestration. **These are important environmental priorities that align reducing agricultural vulnerability with meeting environmental targets.**

Estimates of soil carbon sequestration potential in Vermont farm fields

Based on the information presented in this brief from recent research in Vermont, we can generate rough estimates of realistic potential for soil carbon sequestration in the top 30 cm (1 foot) of agricultural soils in Vermont.

If we assume:

- Average bulk density on farm fields in Vermont is 1.3 g/cm^3(measured by the State of Soil Health Project)
- The current level of soil organic matter in Vermont farm fields is 4.3% (State of Soil Health Project)
- Investments in soil building could increase average organic matter content to 6% in the top 30 cm of the soil profile on hay and corn fields in Vermont.

  There are 34398 hectares of corn and 111288.55 hectares of hay in Vermont (NASS).[x]
- Soil carbon increases by 1.755 MT Carbon per hectare (equivalent to 0.09% organic matter content) each year under best management practices.

That would sequester an equivalent of 937,494 MT CO_2e annually. To put that in perspective, a car in Vermont emits an equivalent of 4.64 MT

CO_2 each year[xiv]. **So, annual soil carbon sequestration at that annual rate is the same as the emissions from 200,000 cars.** At that constant rate, average soil organic matter content would reach 6% over 19 years, offsetting a total of 17,708,234.43 MT CO_2e over that time period. However, soil carbon sequestration does not increase linearly (the rate of accumulation slows down as it gets higher). Our basic estimate could be improved by process-based soil carbon modeling. Here we've provided rough and optimistically realistic estimates based on research in Vermont. They do not incorporate nitrous oxide emissions from associated nutrient management strategies, or carbon accounting at the whole farm scale, but they are still useful.

Based on the information we have available, investment in soil building on Vermont farms could be a short or medium-term strategy that complements other effort to mitigate atmospheric greenhouse gas concentrations. It is important that this strategy be complemented by financial and educational strategies that safeguard the permanence of existing and added soil carbon.

Conclusion

Climate and soil texture contribute to high soil carbon stocks in Vermont. Forests, wetlands and some agricultural soils in Vermont have high soil carbon stocks that should be protected. Crop fields in Vermont present an opportunity to increase soil carbon content, which has the potential to provide other co-benefits. Recent research in Vermont documents the potential for soil carbon gains to be made on many farm fields and offers estimates for carbon sequestration through widespread adoption of best management practices. More research is needed to expand our understanding of how management practices used by farmers in Vermont influence soil carbon content and net farm greenhouse gas emissions. Policy should protect existing carbon stocks, enhance carbon sequestration wherever possible and provide educational and financial supports that safeguard permanence of soil carbon.

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- *University of Vermont Extension*
- *University of Vermont Department of Plant & Soil Science*
- *Gund Institute for Environment*

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Estimating soil carbon gains

1) First, we estimate the annual increased amount of soil organic matter in the top 30 cm of agricultural fields using best management practices, and we assume:

- Average bulk density on farm fields in Vermont is 1.3 (measured by the State of Soil Health Project)
- Best management practices increase soil organic matter by 0.09% points annually

Soil organic matter content x bulk density of soil x depth x area = Metric tons soil organic matter per hectare

0.0009 x 1.3 x 0.3 meters x 10000 square meters/hectare = 3.51 MT SOM per hectare per year

2) Second, we calculate the portion of soil organic matter that is organic carbon using an updated conversion factor of 0.5 from research by Pribyl (2010)[iii].

Soil organic matter content x 0.5 = soil organic carbon content

3.51 MT SOM x 0.5 = 1.76 MT Carbon per hectare per year

3) Third, we use the molecular weights to convert the MT of carbon to equivalent MT of CO_2 (CO_2e).

MT Carbon x (44/12) = MT CO_2e

1.76 MT Carbon per hectare per year x (44/12) = 6.44 MT CO_2e per hectare per year

4) Fourth, we extend that across all hay and corn fields in the state of Vermont. According to the National Agricultural Statistical Service, there are 34,398.28 hectares of corn and 111,288.55 hectares of hay in Vermont[x]. Together, that's 145,686.38 hectares of the 485,622.78 total hectares operated by farms in VT[x].

1.76 MT Carbon per hectare per year x 145,686.38 hectares = 256,408.83 MT C per year

6.44 MT CO_2e per hectare per year x 145,686.38 hectares = 937,494 MT CO_2e per year

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