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Measuring ecosystem services from soil health. Vermont Payment for Ecosystem Services Technical Research Report #1

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Vermont Payment for Ecosystem Services Technical Research Report #1

Prepared for the Vermont Soil Health and Payment for Ecosystem Services Working Group

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EXECUTIVE SUMMARY

Vermont's Act 83 of 2019 identified the need for a payment for ecosystem services (PES) program that would compensate Vermont farmers for providing ecosystem services from agricultural lands, and tasked the Vermont Soil Health and Payment for Ecosystem Services Working Group with making recommendations for the implementation of PES in Vermont. Early on, this effort specifically identified that improved soil health would lead to enhancements in crop resilience, carbon storage, stormwater storage capacity, and reduced agricultural runoff to waters. The ecosystem services the PES working group aspires to incentivize now includes climate regulation (carbon storage and carbon sequestration), downstream flood risk mitigation, climate resilience, water quality, soil conservation and biodiversity.

There are a multitude of approaches to evaluating soil health and the soil processes influenced by soil health. As the state of Vermont explores innovative programs that compensate farmers for soil health and associated ecosystem services, the selection of soil health indicators and quantification methods is a foundational first step that influences other aspects of program design. What is measured determines the ecosystem services that can be inferred, the accuracy of data that informs decisions, and programmatic transaction costs. Simply put, what is measured matters. The PES Working Group identified organic matter, bulk density, aggregate stability, greenhouse gas flux from the soil surface and soil biodiversity as the soil health indicators that would be most closely related to the desired ecosystem services, and contracted with UVM to provide more information on the measurement considerations for these indicators.

In this report, the available methods and costs of measurement for these soil health indicators are discussed in detail. In addition, modeling options are identified. Finally an index that could combine multiple soil health indicators is explored as an option. Overall, this foundational research identified the need for the PES program to integrate both soil health measurements with modeling to validate soil health. Costs for laboratory analysis and labor for these selected metrics were approximately $250 per field, and we identified three analytical laboratories that could provide the soil health analysis.

The contents of this report are intended to support decision-making on the part of the Vermont Soil Health and Payment for Ecosystem Services Working Group about what will be measured in a PES, but do not constrain the group from adding other metrics should they so desire. This decision must balance accuracy and complexity with the cost of measuring the best indicators of performance. These decisions are foundational to other aspects of PES program design.

KEY MESSAGES:

- Soil health indicators selected by a VT PES Working Group Subcommittee can be used as indicators of five ecosystem services of interest: climate regulation, downstream flood risk mitigation, soil conservation, climate resilience and biodiversity. These soil health indicators are organic matter, bulk density, aggregate stability, greenhouse gas flux from the soil surface and soil biodiversity. Based on our research, four of the five metrics are feasibly measurable for a PES: aggregate stability, organic matter, bulk density and biological diversity.
- Soil health is not a strong enough indicator of water quality to be included in a soil health PES.
- Measuring and monitoring soil carbon is achievable. It requires multi-year monitoring of soil carbon, and training in the collection of bulk density measures.
- Measuring and monitoring of greenhouse gas flux from the soil surface is cost prohibitive and time intensive. Weakly to moderately accurate models for greenhouse gas flux exist but may not capture all management practices for Vermont.
- Measuring and monitoring indicators of downstream flood risk mitigation is achievable, but field location and connectivity to waterways determine the provisioning of downstream flood risk mitigation and should be incorporated into program design thoughtfully.
- Soil biodiversity can be measured through changes in soil microbial diversity and/or monitoring of soil invertebrate populations.
- Inherent field location and soil texture influence the provisioning of ecosystem services, and the working group should carefully consider whether payments consider those static characteristics.
- The metrics researched here can be evaluated at the field scale, but some ecosystem services, such as climate mitigation services in particular, could be assessed at the net whole farm scale.
- Using consistent procedures and labs will be important for comparing data over time and between locations. Comparative benchmarking data would be helpful to determine additionality over time at a farm scale, or additionality in comparison to expected optimal ranges and thresholds.
- Measurement costs for this suite of indicators will be approximately $200 to $300 per field. Estimated costs for lab analysis of the selected soil health indicators per field comes to a range of **$68 - $142**, this does not include labor for sample collection or shipping costs to labs for analysis.
    - Organic matter: **$4-8**
    - Bulk density: **$24-$30** (3 subsamples at $8-10 each)
    - Aggregate stability: **$10-24**
    - GHG modeling: $0
    - Biodiversity: **$30-80**
- A soil health index based on these metrics could make determination of payment rates easier. If an index was to be pursued, a facilitated process for determining appropriate weighting and incorporation of site and soil characteristics would need to take place.

INTRODUCTION

During the spring/summer of 2021 a subcommittee of seven Vermont PES Working Group members met to determine a set of soil health measurements that could be used as indicators of ecosystem services for a Vermont PES program. The subcommittee included scientists, state agency staff and a farmer. The group explored lengthy lists of soil health measurements and then discussed further those that indicate the ecosystem services of interest for PES in Vermont. The group also considered challenges such as labor and cost and sought to minimize the number of measurements. The group was able to develop a concise list of five measurements that could be used to indicate five ecosystem services of interest (Table 1). This list was passed along to our team to refine, build out considerations for measurement, modeling and to explore the concept of an index that combines the measurements.

The goal of this paper is to provide background research that will support Vermont PES Working Group members in further refining their list of soil health indicators.

Soil health measurements as indicators of ecosystem services

There is no single measure of soil health. The USDA NRCS defines soil health as the "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans."[1] This definition highlights the dynamic, living and interconnected nature of soil health as a concept. Many biological, physical and chemical characteristics of soil related to ecological function are measured as indicators of soil health. Some laboratories offer suites of tests as soil health testing packages that capture multiple aspects of soil health. The soil health indicators selected for a PES program in Vermont should express the social benefit and ecological function behind the ecosystem services of interest, while balancing any practical challenges and costs that might be associated with each measurement.[2]

The Vermont PES Soil Health Working Group has identified climate regulation, downstream flood risk mitigation, biodiversity, and water quality as critical ecosystem services for Vermont. Measurable characteristics of soils have well established links to some of these ecosystem services, however, the link between water quality and soil health can be tenuous[3,4] . Many water quality conservation practices have soil health co-benefits, but because there is not a consistent causal link from soil health to water quality, and in light of the potential for trade-offs in this regard, a recommendation was made to instead rely on several well-developed tools for assessing water quality outcomes (i.e., VT P-index, APEX). Hence, the working group removed water quality from the list of ecosystem services related to soil health metrics (Table 1).

The selected soil health metrics are dynamic soil properties, which are both measurable and indicative of changes in ecosystem services (Tables 1 and 2). The list of selected indicators is not comprehensive— rather, it is intentionally concise. The subcommittee sought to limit the cost and complexity of soil health measurement, and decided to eliminate indicators that were either redundant or not directly indicative of the ecosystem services. The result is a list of five metrics, and some of the selected soil health indicators can be used to inform multiple ecosystem services. For example, aggregate stability is indicative of three ecosystem services- climate resilience, flood risk mitigation and soil conservation. Importantly, inherent site characteristics, soil texture and vegetative features interact with soil characteristics to influence the supply of

Table 1. Ecosystem services and associated soil health indicators selected by the Vermont Soil Health and PES Working Group. Ecosystem services (column 1) flow to different scales of beneficiaries (column 2) and are influenced by ecosystem functions of healthy soils (column 3). The metrics selected by the working group (column 4) are measurable indicators of change in the ecosystem function, but the list is not comprehensive. Inherent site characteristics, soil texture and vegetative features interact with soil characteristics to influence the supply of ecosystem services (column 5).

Ecosystem Service	Beneficiaries	Ecosystem Function	Selected measurable indicators/ metrics	Mediating site & soil characteristics
Climate regulation	Global	Carbon storage	• Organic matter • Bulk density	• Soil texture • Drainage class • Soil moisture conditions • Artificial drainage
		Respiration	• CO_2 emissions from soil surface	
		Denitrification	• N_2O emissions from soil surface	
Downstream flood risk mitigation	Downstream communities	Infiltration	• Bulk density • Aggregate stability	• Location (proximity and position relative to water, connectivity) • Depth of soil • Soil type/texture • Slope • Artificial drainage
		Water storage	• Organic matter	
Soil conservation	Farm, Future generations, Downstream communities	Soil aggregation & cohesion	• Aggregate stability	• Depth of soil • Soil type/texture • Slope
Climate resilience	Farm & Foodshed	Available water capacity	• Organic matter	• Soil type/texture • Slope • Drainage • Depth of soil • Hydrologic connectivity
		Soil aggregation & cohesion	• Aggregate stability	
Biodiversity	Local & global	Foundation for other ecosystem functions & conserves genetic resources	• Biodiversity in soil	• pH • Soil texture • Land use history

many of these ecosystem services. While the flow of ecosystem services from any given site will be limited by those static characteristics, the selected indicators are sensitive to dynamic characteristics of soil that can be influenced by management. The degree to which static site and soil characteristics are taken into account in a PES program is an important decision for the working group to consider. The scope of this report is limited to documenting practical considerations for the five soil health indicators selected by the subcommittee:

1. Organic matter content
2. Bulk density
3. Aggregate stability
4. Greenhouse gas emissions from the soil surface (N_2O and CO_2)
5. Biodiversity in soil

Below, we explore these measurements as indicators of the ecosystem services important to Vermont and summarize important quantification considerations.

Table 2. Simplified table summarizing measurement considerations for each soil health indicator. These considerations are explored in depth in the report.

Indicator	Details	Who conducts test[1]	Cost	Scale	Feasibility	Accuracy
Organic matter	Loss on ignition	All soil testing labs	$4-8 per sample Labor costs: low.	Field	High (Commercial)	Medium
Bulk density	Collect intact soil cores and oven dry. Tools and training required.	UVM AETL, DairyOne	$8-10 per sample, three per field, plus additional tool costs. Labor costs: high.	Field	Moderate	High
Aggregate stability[2]	Assess % of water stable aggregates from either simulated rainfall or agitation in water	UMaine, Missouri Soil Health Center, Cornell, (could be added by UVM)	$10-$24 per sample Labor costs: low.	Field	High (Commercial)	Medium
GHG emissions from surface	Photoacoustic gas analyzer	Research technicians needed for frequent in-field measures	Direct measurement is cost prohibitive. Labor costs: high.	Field	Low	Low
	Modeled estimates[3] using COMET, Daycent or DNDC	Anyone can access COMET. Some models require technical knowledge or training.	The cost of modeling is time. Labor costs: high.	Field or farm	Moderate	Low
Biodiversity in soil[4]	Ecoplates: carbon substrate utilization test on a standard composite soil sample in lab	UVM research labs (Neher and Darby Labs, not commercial)	$30.00 per sample, plus lab tech time. Labor costs: moderate.	Field	Moderate	Moderate
	PLFA[5]: Phospholipid-derived fatty acid test on standard composite soil sample in lab	Missouri Soil Health Center, Ward Labs, Earthfort	PFLA is $50 - $80 per sample. Earthfort is > $100. Labor costs: low.	Field	High (Commercial)	Moderate
	Invertebrate monitoring: collection and identification of invertebrates or bait lamina test system	Soil ecologists (such as Deb Neher at UVM)	Generally expensive-- requires time, training and equipment. Labor costs: high.	Field	Moderate	Moderate

1. Laboratory links: University of Vermont Agricultural and Environmental Testing Lab: https://www.uvm.edu/extension/agricultural-and-environmental-testing-lab ; University of Maine Soil Testing Lab: https://umaine.edu/soiltestinglab/ ; Cornell Soil Health Lab: https://soilhealth.cals.cornell.edu/ ; Missouri Soil Health Assessment Center: https://cafnr.missouri.edu/soil-health/ ; Ward Laboratories: https://www.wardlab.com ; Earthfort Lab: https://www.earthfort.com
2. For aggregate stability, visual soil assessment or slake tests can be used in the field but are described qualitatively and are hard to compare across locations and over time.
3. Models do not include all possible management (grazing & vegetable systems are poorly represented)
4. Samples for biological analysis are time and temperature sensitive and require special handling. Deb Neher, soil ecologist from UVM should be consulted to design monitoring of soil biodiversity.
5. The Earth Fortification lab uses a test that is similar to PLFA-- considered more complex but more detailed.

CLIMATE REGULATION

Soil health influences *climate regulation* as an ecosystem service through its overall impact on the balance of atmospheric greenhouse gasses. This includes 1) the storage of carbon in soil that could otherwise be released as CO_2, 2) an increase in soil carbon that is sequestered from atmospheric CO_2, and 3) the release of greenhouse gasses during biologically mediated processes, such as CO_2 from respiration, and N_2O during denitrification. Methods for measuring soil carbon content are well established and broadly implemented. Methods for measuring greenhouse gas emissions from soils are challenging, require careful interpretation, and are generally expensive in technology and technician time. Improved technologies for measuring both are currently under development. Moderately accessible models for this ecosystem service at the field level exist but may not capture all management scenarios for Vermont.

Measuring soil carbon storage

A *soil carbon stock* is an amount of carbon in a known volume of soil. To calculate soil carbon stocks the *soil carbon content and bulk density must be known*. Stock estimates for different depths are not comparable, so establishing a standard depth is important. The standard depth of measurement for soil carbon stocks established by international standards is 30 cm,[5] and this is the depth to which soil carbon stocks were measured for the State of Soil Health project[6]. This differs from routine soil test depths in Vermont, which are generally taken to 15 cm.

Soil carbon is in two forms: organic and inorganic. Inorganic consists of mineral forms, whereas the organic carbon portion originates from living biological material and is the dynamic portion influenced by management. Organic carbon is approximately half of soil organic matter (conversion factor of 0.5)[7], and soil organic matter is routinely and easily measured in standard soil tests. Standard soil testing labs use the Loss on Ignition (LOI) procedure to measure organic matter content. This is a fairly accurate and low-cost test, and samples can be collected easily from the field without special equipment, and then submitted to a lab. Soil testing labs at UVM, and in neighboring states, are equipped to conduct this test[8]. As a stand-alone test, the cost per sample for LOI is within a range of $4-$8 from regional labs, including UVM, UNH, UMaine and DairyOne in Geneva, NY.

LOI measures the weight loss of dry samples subjected to an oven at ~360-375°C. A similar procedure called Dry Combustion, at a temperature of ~900°C can measure total carbon, inclusive of inorganic carbon. Dry Combustion is recommended by NRCS as more accurate[9], but is more costly, at $20 per sample from Cornell. Some researchers have pushed to use Walkey-Black wet chemical procedure to measure active carbon as an indicator of change. While the active carbon test is sensitive to early changes, it does not capture all forms of organic matter.

Bulk density is a measure of the physical mass of soil in a given volume. In order to measure bulk density, an undisturbed core is collected, oven dried and weighed. The metric for bulk density is the dry weight divided by the volume of the core (g/cm^3). A minimum of three cores per field should be collected. Bulk density for a given depth can be measured as an entire core of the given length, or as a stratified sample, with multiple short cores collected to represent the entire depth of interest. Specialized equipment for collecting undisturbed cores is available, and somewhat costly, at $400-$1000. Collecting the cores also requires more time than standard soil sampling. Based on our experience, depending on conditions this can take 1-4 hours per field using hand powered tools. Collecting undisturbed cores requires extra time and care to ensure the cores are collected in a uniform and comparable way. Processed samples in the lab costs approximately $5-$10 and is available locally from the UVM AETL and DairyOne. Collection of accurate bulk density samples requires training and skilled labor that should be accounted for on top of lab processing costs.

An alternative approach to measuring bulk density is build a local model that uses measured organic matter, soil texture, penetration resistance and soil moisture to estimate bulk density. A training dataset would need to be collected and used to build a predictive model. However, after the model was developed, bulk density could be inferred from these parameters that are easier to measure. This exact approach has not been used for a soil-health program, but several researchers have built reasonably accurate models linking soil characteristics, soil water content, penetration resistance and bulk density for various agricultural regions.[10,11]

New tools are currently under development using machine vision technology to provide rapid estimates of soil carbon content using a probe. Examples include Yard Stick[12], and Stenon[13]. Yardstick is currently undergoing field calibration in the US, and reports from Stenon technology calibration indicate it is inaccurate for soils with fine textures (clay), and only measures to a maximum of 3% soil organic carbon[14]. While the technology is not currently ready and suitable for Vermont soils, the Vermont Soil Health PES should keep apprised of this technology development, as well as the potential for near and mid infrared spectroscopy to reduce the costs of quantifying SOC content.

Measuring carbon sequestration

Soil carbon *sequestration* is the capture of atmospheric carbon in photosynthesis by plants, which is subsequently incorporated into the organic portion of soils through decomposition. If the additions of organic carbon are greater than the losses through respiration and harvest, a net gain in soil carbon can be achieved over time.

Measuring the change in soil carbon requires that evaluation be able to compare changes over time. This means that baseline data is needed, as well as follow up measurements at a later time. Changes in soil organic matter from management are detectable at multi-year intervals, often taking 3-5 years to show up in measurements. Soil organic matter also fluctuates seasonally, so it requires that sampling be conducted at the same time of year to confirm changes in soil carbon levels. Annual sampling would provide greater accuracy and help identify potential year-to-year variability. However, sampling at 2–3-year intervals would be sufficient.

Additionally, the origin of organic matter must be considered. Organic matter additions from offsite will influence soil carbon content, but in some cases may not always be considered as sequestration within the boundary of the field. This is an important consideration for PES program design. Farmers can reduce atmospheric carbon in two ways: by increasing the rate at which their land captures carbon, and/or by slowing the rate at which soil carbon returns to the atmosphere. Applying compost made off-site, for example, increases soil carbon content, but does not necessarily increase carbon uptake or reduce losses. On the other hand, growing high biomass cover crops can increase carbon uptake, and reduced tillage can reduce carbon losses. Building assessment or accounting tools for carbon being brought onto the farm may add accuracy but would likely add complexity in reporting and verification.

Changes in bulk density should likely not be included in calculations of carbon sequestration. A change in bulk density has opposite implications for the supply of other ecosystem services. Increases in bulk density would measure greater soil carbon stocks but reduced infiltration capacity. Reductions in bulk density would indicate increased infiltration but measure smaller carbon stocks. In order to eliminate a penalty in terms of carbon storage for farmers who reduce compaction in their fields, an assumed reference bulk density value could be used for carbon storage, otherwise the program may inadvertently incentivize compaction

Influence of site characteristics on soil carbon

Soil texture influences the capacity for sequestration and the upper limit of soil carbon content that may be achievable at any site. Finely textured clay soils have a high affinity for soil carbon and have higher soil carbon content when compared with coarse sandy soils. Figure 1 shows how recent organic soil carbon content measured on Vermont farms in the same production differs by soil texture. For Vermont PES, this means that *soil texture limits the potential for soil carbon content at each site, and expectations for sequestration should be differentiated by soil texture.*

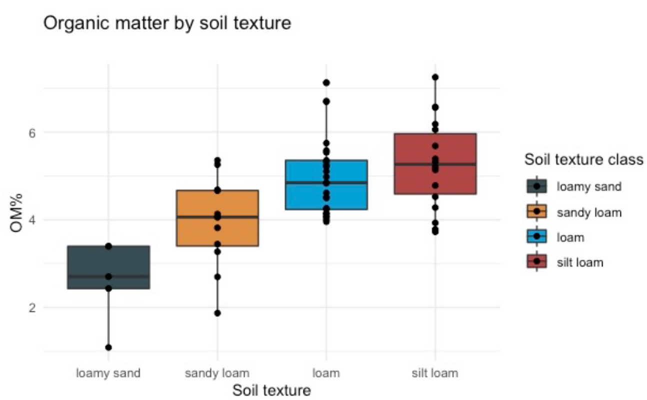


Figure 1. Soil organic matter content differs by soil texture. This data is from 60 corn fields in northwestern Vermont that participated in a Soil Health CIG study led by Dr. Heather Darby in 2020.

Measuring N_2O and CO_2 flux

Overall, measurement of gaseous flux from the soil surface requires costly equipment and staff time, and is impractical for monitoring and quantification in a Vermont Soil Health PES until technology changes significantly. Measurement tools can capture a subsample of gaseous flux from a point on the soil surface over a small time period. To estimate an annual impact on GHG flux, multiple measurements at multiple points in time must be collected and used to infer GHG flux across the field and between measurement times. A single photoacoustic infrared gas analyzer tool alone costs \$500-\$5,000.

Modeling climate regulation

Greenhouse gas emissions from soil, including nitrous oxide, carbon dioxide and methane, are highly sensitive to soil water and air conditions, and often occur in sharp pulses. Modelling these outcomes is complicated and subtle, and while there are important relationships between soil health parameters and gaseous emissions, these are not easily distilled. Developing estimates for how soil-health parameters (e.g., soil organic matter and bulk density) impact gaseous emissions would be best accomplished in complex, hard-to-use models such as DayCent or DNDC. The USDA's COMET-FARM model can generate predictions of greenhouse gas emissions from soil, based on a wide range of practices. However, COMET cannot incorporate changes in other soil-health indicators.

There is a lot of interest in estimating soil carbon based on imagery, but this has not proved accurate at local scales. In 2021, the Northwest Crop and Soils team at UVM Extension compared measured soil carbon stock data from the NRCS Rapid Carbon Assessment with NASA SMAP and UN FAO global soil carbon maps, but found no significant correlation. In order to use imagery to predict soil carbon content accurately, it would require extensive calibration and validation with local on-the ground measurements. For a Vermont PES, this means significant investment into sampling, analysis and development of a tool that could accurately infer subsurface soil characteristics from land cover images would need to take place, without knowing if the tool could even work accurately eventually.

DOWNSTREAM FLOOD RISK MITIGATION

Soils have the capacity to infiltrate, absorb store and retain water, and can therefore mitigate the storm water runoff volumes that impact peak flows, and potentially downstream communities' flood risks[15]. Enhanced soil health can influence the hydrologic response of agricultural fields and reduce storm water runoff volumes by altering the infiltration and water holding capacity of the soil. Biological activity and organic matter change the physical structure of soil and the way it interacts with water by increasing aggregation, pore space and the sponge-like characteristics of soil. Soil structure and the presence of macropores influence infiltration and drainage, but a field's proximity and connectivity to waterways, depth of soil, clay content, antecedent moisture condition, soil texture, surface cover and the presence of artificial drainage will also influence a field's potential to contribute to mitigating downstream flood risk. Finally, the relative location of a field to a downstream community determines if there is potential for delivery of flood risk mitigation as an ecosystem service.

Measuring indicators of downstream flood risk reduction

Tools to directly measure infiltration in the field exist but are time consuming to conduct and there are many challenges to ensuring accurate and comparable measurements. Bulk density, organic matter content and aggregate stability are indicators of the dynamic changes in soil structure that influence infiltration, that are more easily measured. Aggregate stability can be a predictor for infiltration rate because the two have been so well correlated[16]. However, clay content and bulk density have been shown to have a stronger influence on infiltration rates than aggregate stability[17], and organic matter content often plays a significant mediating role[18]. Thus, aggregate stability can be an indicator to complement other measures, but bulk density and organic matter content may be more direct indicators.

Bulk density is a measure of soil mass by volume, and an indicator of soil compaction[19]. A decrease in bulk density directly indicates an increase in pore space and infiltration capacity. Considerations for measuring bulk density are described in the Climate Regulation section above. Processing samples in the lab costs approximately $8-$10 per sample and is available locally from UVM AETL and Dairy One. Three cores should be taken from each field.

Increases in *organic matter* may have an effect on soil water content at saturation, field capacity and available water capacity. A recent meta-analysis of relevant research found that although there are studies that show large impacts of organic matter on soil water, there are also studies that document very limited effects[20]. On average, increasing a soil's organic matter content by 1 percentage point increases soil water content at saturation by 2.95 percentage points, and plant available water capacity by 1.16 percentage points, though this factor differs by soil texture[13]. Considerations for measuring organic matter content are described in the Climate Regulation section above. As a stand-alone test, the cost per sample for LOI is within a range of $4-$8 from regional labs, including UNH, UMaine and DairyOne.

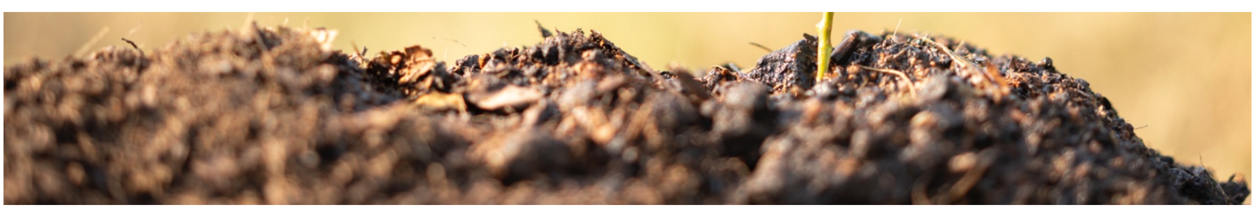
In the case of soil conservation, erodibility is only influenced by soil organic matter concentrations near the soil surface. Given the low costs of measuring soil organic matter, it may be feasible to take LOI measurement for different depths—one for the 0-15 cm layer, another for the 15-30 cm layer, and potentially deeper. This would allow the program to focus in on the impact that soil organic matter near the surface has on soil conservation, and give participating farmers insights into how soil carbon can be distributed through the soil profile. The depth of the A horizon may change. This is likely too complex to add to a PES program, but should be understood and considered to come degree. Erosion may reduce the depth of the A horizon, inputs or a reduction in bulk density may increase the depth of the A Horizon.

Aggregate stability is a measure of water-stable aggregates. It is expressed as the percent of aggregates of a specific size that withstand exposure to either a simulated rainfall event[21], or a submerged agitated water environment[22]. This is included as part of the Cornell Comprehensive Assessment of Soil Health and the University of Maine Soil Health testing packages, and also available from the Missouri Soil Health Testing program. Individual aggregate stability analysis from these labs cost $10 - $24, and may become available from UVM in the future. Comparisons of change over time need to use measurements from the same procedure, so switching between labs is unadvisable.

Modeling downstream flooding

The NRCS curve number method is the easiest and simplest tool for estimating how land-use impacts runoff. The method uses a lookup table and a simple calculation to generate estimates of runoff from a storm event with a given rainfall based on hydrological soil group, land use, and moisture condition. This method cannot directly incorporate soil health indicators.

As part of the Ecosystem Services Valuation Report (Task 5) we are using two methods to estimate soil-health impacts on downstream flooding: the Green-Ampt method and simple increase in soil water-holding capacity. The Green-Ampt method requires measures of porosity, plant available water capacity and saturated hydraulic conductivity. These indicators can be modelled based on soil texture, bulk density and organic matter content. By simulating a wide range of storms, on a wide range of soils and a gradient of soil-health indicators we will be able to create a simple tool to estimate the impacts of a given amount of soil-health improvement on runoff, that can be translated back into an impact on a curve number. For a simple method, we can assume that the major storms which result in large flood risk generate saturated conditions across most soils. From this, we can assume that reductions in flood flow due to soil health are proportional to the increase in unused plant available water capacity at the beginning of the flood event. Plant available water capacity can be modelled as a function of soil texture, soil organic matter and bulk density.



BIODIVERSITY

Soil biodiversity is a supporting ecosystem service that provides the foundation for the ecological processes and functions of the living portion of the soil[18]. The diversity of microorganisms and fauna in soil plays a central role in processes such as the formation of structure, degradation of pollutants, cycling of carbon and nutrients, decomposition, regulation of plant communities, disease suppression and pest regulation[23, 24].

Soil biodiversity measurements are often challenging to interpret and are only useful if understood relative to an optimal condition. Ideally, a locally relevant reference point from an undisturbed or desired site could be used as the optimal condition. Spatial set up of monitoring as well as sampling frequency and repeatability are important considerations for planning measurements. The FAO advises that soil biodiversity measures be "sensitive enough to reflect the influence of management and climate on long-term changes in soil quality but not be so sensitive as to be influenced by short-term weather patterns and robust enough not to give false alarm and be meaningful, resonant and easy to understand."[19]

The approaches to measuring soil biodiversity include broadly either measures of functional diversity or amount of biological activity. Functional diversity can be measured through carbon substrate tests, PLFA or invertebrate counts. Measures of the amount of biological activity, though not directly indicators of diversity, are sometimes inferred as indicators of diversity. This includes measures of microbial biomass and respiration (not explored in depth here).

Measuring microbial diversity

Ecoplates measure the metabolic activity of soil micro-organisms using 31 different carbon substrates. Soil from a standard composite soil sample must be moved on ice from the field to lab as quickly as possible. The soil is then put into solution and applied to a plate of 93 wells, with the carbon substrates in triplicate. The plate is incubated and read for the degree of metabolic activity and the number of substrates consumed. The results of Ecoplate analysis can be easily interpreted as a metabolic niche diversity index, a Shannon diversity index and a metabolic rate. Two labs at UVM have Ecoplate readers currently being used for research only, (Neher and Darby labs), but could potentially be accessed for a Vermont PES. Individual plates cost approximately $30.00, and with staff time, likely cost $35-40 per sample when processed in bulk.

Phospholipid-derived fatty acid (PLFA) tests offer a snapshot of the quantity of microbial biomass, and presence of certain functional groups, at the time of sampling. PFLAs are found in cell membranes, with certain fatty acids associated with different organisms. Quantifying these fatty acid contents in a soil sample can therefore indicate the size of specific microbial groups as well as the entire microbial biomass. The test indicates an amount of microbial biomass in g/g or nmol/g, and a functional group diversity index. The results can be used to estimate proportions of microbial types such as actinomycetes, arbuscular mycorrhizal fungi, rhizobia, saprophytic fungi and protozoa. Ward laboratories charges $80.00 per sample for PLFA, and the University of Missouri Soil Health Center charges $50.00 per sample.

Figure 2. An inoculated Ecoplate with 31 different carbon substrates in triplicate.

Earthfort Labs conducts a microscopy-based evaluation (not PLFA) that yields similar results, but costs upwards of $100 per sample. Results are not comparable across labs.

Monitoring soil invertebrates

Soil invertebrates play significant, but largely overlooked, roles in the delivery of ecosystem services. They are enormously diverse, from microscopic mites (Acari), to nematodes, springtails (Collembola), woodlice (Isopoda), earthworms (Haplotaxida/Lumbriculida) and beetles (Coleoptera). They perform a wide range of functions that contribute towards soil health, affecting organic matter decomposition and soil structure through shredding, microbial inoculation, and bioturbation activities, and influencing plant communities through selective herbivory. The breakdown of dead or decaying plant and animal material by invertebrate decomposers and detritivores provides a central input of nutrients and energy for soil processes. Invertebrates are sensitive to changes in soil conditions and are therefore valuable indicators of soil disturbance. Different taxa have varying sensitivities to soil characteristics, resulting in changes in taxa richness[25], but the overall abundance of soil invertebrates has also been shown to be affected. Invertebrates are abundant, relatively easy to sample and may respond quickly to soil disturbances. Samples can be extremely time and temperature sensitive and require someone knowledgeable to do identification.

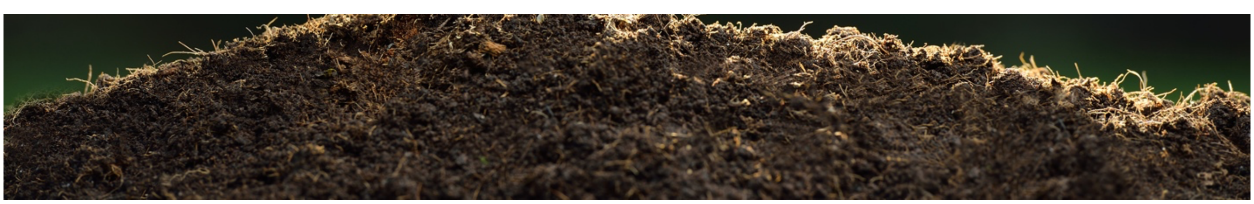
To extract *microarthropods* (Acari, Collembola, Enchytraeids), Berlese-Tullgren apparatus may be used whereby soil samples are placed on a gauze in a funnel with a heated light suspended above. As the heating and drying effect occurs, soil animals move down the funnel into a collecting vessel beneath. This method is cheap and straight-forward, but the processing of samples is limited by the number of funnels available, some organisms may desiccate before they can move out of the funnel. A Winkler extractor may also be used in which the soil sample is suspended in a mesh bag over a collecting vessel in ambient conditions (room temperature/no light). Pitfall traps (collecting vessels buried flush with the surface of the soil and left in place for 24 h) have been shown to be the most effective technique in capturing surface-active invertebrates including Diptera, Coleoptera, Chilopoda, Diplopoda, Hymenoptera and Orthoptera[26]. Training and dedicated facilities are required to do this procedure.

Earthworm densities are most effectively measured by a combination of extraction and hand sorting; however the application of formalin extraction is not recommended due to its toxicity. Extraction solutions using mustard or onion have been found to be effective, inexpensive and nontoxic alternatives.[27] Although hand sorting alone has reduced efficiency, particularly for deep-burrowing anecic species, it is a practical and achievable technique for farmers. Earthworms should be counted in early autumn or late spring, and not in extreme weather conditions or following manure/compost application. A 20 x 20 x 20 cm hole can be dug with a standard shovel, and the soil placed on a plastic sheet. The soil is searched by hand and earthworms are placed into a plastic bag, counted and recorded, and then replaced with the soil back into the hole. There are three functional groups of worms; epigeic (surface), endogeic (topsoil) and anecic (deep burrowing) and these may be easily identified and recorded with training. Basic earthworm counts can be more accessible than other invertebrate monitoring programs, but still require time and training.

Dung beetles (family Scarabaeidae) have an important role in dung decomposition and nutrient cycling on pastureland and can be identified by their clubbed antennae and strong paddle-like legs. Dung baited pitfall trapping, flotation, or visual searching may be used, all of which are inexpensive methods, although setting up pitfall traps may be time consuming. Dung beetle species and numbers vary according to the time of year, soil type, grazing management, shade and age of dung. A number of sampling sites should be selected to cover different habitats at set times of year. To perform simple counts, farmers may place a dung pat into a white tray and break it apart to count the beetles, or into a bucket of water whereby the beetles will float to the surface. However, these techniques will only sample endocoprid beetles (which live inside the dung pat) and not paracoprid beetles (which tunnel into the soil). Dung-baited pitfall trapping will attract a more accurate representation of these species. Dung beetles are slow moving and often play dead: fast moving species in dung are likely to be Hydrophilids or Staphylinids. Identification into functional groups (endocoprid and paracoprid) is important when considering ecosystem service provision and is straightforward based on body shape. Relative abundance of some invertebrates is not comparable across production systems. For example, dung beetles are important to assess in pastureland, but less so elsewhere.

Finally, the *bait lamina test system* may be used to assess both soil microbial and soil invertebrate activity, by using soil fauna feeding activity as a proxy. Bait lamina strips are 1 mm × 6 mm × 120 mm PVC strips which have sixteen 1.5 mm holes spaced 5 mm apart along their length. The holes are filled with a standard bait of cellulose powder, wheat bran and activated charcoal (70:27:3). Strips are inserted vertically into the soil and when removed, the proportion of bait eaten reflects the soil faunal activity in the soil. This technique provides a comparable and quick screening of soil biological activity, however may be somewhat costly ($500-$1000 per farm) and is strongly dependent on soil type and moisture.

All invertebrate monitoring methods described here require training in methods and identification, plus the time to conduct monitoring.

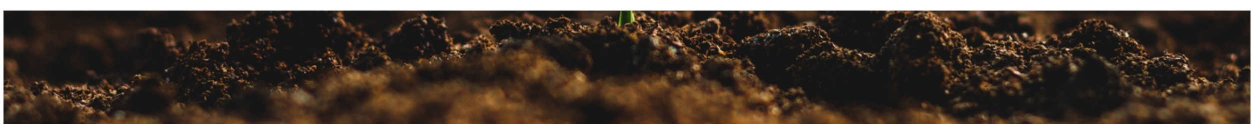


SOIL CONSERVATION & CLIMATE RESILIENCE

Soil conservation and climate resilience are complementary ecosystem services to those above. The indicators selected by the working group are also logical indicators of the potential for soil loss (erosion) during precipitation and flooding events (*aggregate stability*), and drought resilience (*organic matter content, bulk density, and aggregate stability*). Aggregate stability is a direct measure of soils' resistance to erosion from forces of water and is an appropriate indicator for soil conservation. Site and vegetative characteristics are also important here. Likewise, aggregate stability is a good indicator of the way enhanced soil heath contributes to soil resilience to heavy precipitation events. As well, greater soil available water capacity increases crop resilience to drought events, and while this is strongly influenced by soil texture, organic matter content, aggregate stability and bulk density are also indicators of soil water holding capacity. We consider them important, but auxiliary to the primary ecosystem services that the working group has focused on.

Modeling soil conservation

Soil loss (erosion) can be estimated using one of many versions of the Universal Soil Loss Equation (USLE). The MUSLE (Modified USLE) may be most useful for our purposes because it calculates the R (runoff) factor in a way that can allow us more flexibility to incorporate soil-health changes. RUSLE2 (Revised USLE) is already widely used in Vermont and can likely be transformed into the MUSLE[i]. Soil health indicators influence two components of this model. First, the soil erodibility factor (K) can be estimated using soil organic matter levels and soil intrinsic qualities, using existing empirical equations[28] [29]. Secondly, the USLE also uses total runoff and maximum runoff rate for each storm as an input. These parameters could be simulated through the methods described for flood control. A tool to estimate the soil K factor based on soil series and soil organic matter content could be developed relatively easily. Developing estimates of overall soil erosion changes due to soil-health based changes in infiltration and runoff would be a much more difficult task and would likely require extensive empirical or modelling research.



CONSIDERATIONS FOR CREATING A SOIL HEALTH INDEX

The PES work in Vermont is based on a concept of soil heath that is not a discrete characteristic or a single measurable attribute. While this reflects the dynamic and complex nature of life in the soil, translating that complexity into policy and programming could create a prohibitively complex PES program. However, if a single representative number or score could be determined to represent multiple metrics together, it could simplify a payment scheme. This concept is referred to as an index-- an index is a number that represents a combination of multiple metrics. The creation of a Soil Health Index for Vermont may be necessary in order to translate measures of multiple soil characteristics into appropriate PES program compensation.

The quest for a single number that could represent the combination of multiple attributes has been pursued by others, most prominently by the Cornell Assessment of Soil Health (CASH)[30]. Cornell's test created scores for each measured attribute, and an overall score based on all

[i] RUSLE calculates erosion as a function of rainfall energy, whereas in MUSLE the rainfall energy factor is replaced with runoff factors.

measured indicators. CASH scores reflect a soil's quality relative to a regional assessment conducted by Cornell researchers. These scores are nationally recognized and used as indicators of soil health in practice by farms and in academic publications.

The indicators selected for a PES program (Table 2) in this report overlap with the CASH test metrics to some degree. Aggregate stability and organic matter directly overlap with CASH. The CASH test uses a penetrometer to evaluate compaction, which measures soil physical characteristics similar to bulk density[ii]. Penetrometer readings are easier to take than bulk density samples, but are considered less accurate, especially in clay soils. The CASH test evaluates biological activity through measures of respiration and active carbon, which are related, but are not direct measures of soil biodiversity. The CASH test provides similar information to the indicators explored in this report and was developed collaboratively to harmonize soil health measurement protocols at the regional scale. The CASH test should be considered by the PES Working Group as an option for Vermont that would allow regional data comparisons, and has undergone extensive development.

The CASH, or similar SASH[31] approach, to indexing and creating scores relative to a regional baseline range could be applied for our work in Vermont. This requires determining an expected range for optimal performance from which to compare soil metrics, differentiated by soil texture. Test results could be given a ranking or score for each metric in relation to this optimal range. Determining ranks for each metric allows the diverse measurements to be compared and combined.

In order to create a single number to represent soil health in Vermont, an index that combines the measurements of interest would need to be developed. In this case, the working group would need to determine a rationale behind weighting of each soil health metric. This could be based on the ES valuation research being conducted for this project by T. Ricketts and B. Dube for Task 7, or through a facilitated process. The work to develop ranking and weighting should be undertaken with ample time, expertise and resources.

There are concerns that existing index tools that have been previously used in Vermont loose information valuable to farmers and are not useful for informing what changes should be made. Including a personalized explanation and break down to each farm could help the index be useful to farmers. Working group members have expressed interest in having each thing measured be considered, tracked, and reported separately. However, an index could simplify program payment design. Both types of information, the index and individual scores, could be developed and shared with farmers and PES program administrators.

[ii] Early development of the CASH test included bulk density as a recommended primary indicator of soil health. See: http://www.nnyagdev.org/PDF/SoilHealthFSPart2.pdf

CONCLUSION

In this paper we explored measurement and modeling implications for a pre-determined list of soil health indicators. Based on our research, four of the five metrics are feasibly measurable for a PES: aggregate stability, organic matter, bulk density and biological diversity. Notably, direct measurement of greenhouse gas emissions is cost prohibitive and not recommended for inclusion in measurement for PES. A program will either need to adopt a modeling approach, or drop this from the scope of the program. Greenhouse gas emissions from soil biological processes are highly influenced by management and in some cases can offset soil carbon gains towards climate regulation ecosystem services[32], so they should be included if possible. The research conducted for this report does not preclude the VT PES Working Group from changing or adding new soil health metrics of interest to their list.

Based on our research, there are some key decisions a PES program must make about the measurable indicators and analysis, and we outline them below. Aggregate stability and soil organic matter are the easiest and cheapest measurements to conduct and can be added to routine field soil sampling. Aggregate stability analyses differ by lab, so a commitment to a single procedure should be made. Measurements of bulk density and biodiversity are more costly and take more time. Consideration of the costs of this data against the value the data brings to the program should be carefully considered. Ecoplate analysis is the lowest cost approach for biodiversity assessment, but is not currently commercially available, so either some investment in making it available in Vermont needs to be pursued, or the more expensive PFLA test could be adopted. Alternatively, a lower cost measure of biological activity or abundance, rather than biodiversity could be adopted instead, but would not be an indicator of soil biodiversity.

Measurement costs for this suite of indicators will be approximately $200 to $300 per field total. Our research estimates the cost of laboratory analysis for all of the measurable indicators within a range $68 - $142 per field, plus approximately $150 in labor and equipment per field for bulk density and biological sample handling. Further work to determine the exact labor costs should be conducted. This labor estimate is based on our experience conducting the State of Soil Health sampling in Vermont in 2021, which used a human scale bulk density sampling equipment and batches of Ecoplates at UVM. Should a larger and more long-term sampling effort associated with the PES program be pursued, mechanized bulk density sampling equipment may save time and costs at scale in the long term. Farmer engagement in the sampling work may reduce the potential programmatic labor costs.

Should the PES Working Group decide to measure the other soil health indicators explored in this report as part of a PES program, there a few practical pathways for measurement and analysis that emerge from our research.

First, the Missouri Soil Health Center may be the only lab that currently commercially offers all of the desired metrics, including bulk density sample analysis, soil texture and PFLA for biological diversity [33]. A Vermont PES program could decide to use this lab at a cost of approximately $181 in total lab fees, plus the cost of bulk density sample collection and shipping, for a total up to approximately $300 per field. This is the simplest approach. However, the aggregate stability measures from this lab may not be comparable with the CASH aggregate stability results which have been widely used in Vermont already. Interpretation of those results for relevance in Vermont would still need to be developed.

Second, soil health testing services within Vermont (likely UVM AETL) could be expanded to provide commercially available analysis that meets the needs of a VT PES. The Missouri Soil Health Center was developed through a collaboration between the University of Missouri, NRCS and Missouri state agencies, and a similar approach could be used here. This could provide closer feedback and efficiency between sample analysis, interpretation for a PES program, and the ease of model development based on local data. Aggregate stability and a biological diversity analysis are the only things that would need to be added to the current AETL soil package. Upfront investments in laboratory capabilities would be needed, but its likely the per field lab analysis cost would be similar or less than the other approaches we've outlined, potentially down to $100 per field. Its possible the state could subsidize soil testing costs at this lab for farmers in Vermont as has been done in Missouri[34], or simply reimburse famers who participate in the program.

Third, the program could use a combination of the CASH test and another lab to measure all of the selected indicators. This is the approach that the Vermont State of Soil Health project took[6]. The cost per field for this project was approximately $250. The advantage in this scenario is that we can compare Vermont soil health metrics to soil health assessments nationally that also use CASH, and we could use the previously conducted CASH tests in Vermont (over 700), to develop a ranking and index. If we choose to develop a new test package, or use the Missouri lab, we will likely need to collect a new set of data in order to develop an expectation for optimal ranges.

For all of these scenarios, the interpretation of metrics for optimal ranges within the State of Vermont is needed. This is work that has been started by the Vermont State of Soil Health project[6], but would need to be refined for the PES needs. The consideration of whether soil health testing services within the state of Vermont should be improved to serve the needs of a Vermont PES is an important decision foundational to PES program development. This may have advantages for Vermont beyond the PES and has been recommended recently by UVM researchers[2].

Modeling has been adopted by other performance-based PES programs, and this offers an advantage of lower costs when compared to direct measurement. Our research shows that existing modeling tools can easily model the impacts of some of the soil health practices on the ecological processes of interest. The soil-health parameters that are feasible to measure - soil organic matter, aggregate stability and bulk density can also be used to predict changes in the ecological processes of interest. A practice-based program would require work to consolidate existing models into a single tool to streamline farmer data-entry. A performance-based program would require additional modelling and empirical work to build or modify a soil-health index, and estimate its relationship to the ecosystem processes we are interested in. Based on our work, we recommend that a new or modified models could reduce the costs of sampling for a PES program, however, field data must be collected to both develop some of these models or to input into the model in order to estimate other soil health parameters. The development of a soil health index is likely needed regardless of the extent to which a program uses modeling or measurement to inform payments.

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