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Resilient Soils for Resilient Farms: An Integrative Approach to Assess, Promote and Value Soil Health for Small- and Medium-Size Farms

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I. Summary of approach and results

Our team was a collaborative group of academic, extension and doctoral student researchers who met internally and conducted an IRB-approved survey that engaged with myriad stakeholders. The result was a clear trifecta on relative timing of soil health initiatives: 1) Stakeholders (91%) embrace soil health and believe soil health should be the top priority for UVM research and outreach. 2) Existing policy demands farmers assess elements of soil health every two years for nutrient management plans. 3) Only a subset of desired metrics is available at commercial laboratories, most soil analyses are sent out of state to Maine or New York, and most data are privately held instead of deposited into public databases. Together, these three findings indicate that soil health be a central focus of UVM's ARS program. Yet, due to attrition, there are no longer any UVM faculty dedicated to updating the 30-year-old soil recommendations upon which regulations rely. There is opportunity for university-government-community partnerships and expanded employment opportunities in Vermont if collaborative resources were assigned to soil health.

II. Background on approach, measures or indicators chosen

Healthy soils are critical to produce food for the world's population (Stott and Moebius-Clune 2017) and to sustain the vital life support functions of healthy ecosystems upon which all species depend (e.g., Lal 2016, Stavi et al. 2016). Originally, soil health was monitored for only its chemical and physical properties, e.g., the nutrients it contains, size of soil particles (aggregate size), soil drainage, and water holding capacity. It is only relatively recently that we have acknowledged the immense role of biology and attempted to monitor the ecological functions that soil food webs orchestrate. Biological measurements have been underrepresented in monitoring programs, and the rudimentary measures that are measured by existing programs are challenging to interpret because calibrations are incomplete or missing (Fierer et al. 2021, Larkin et al. 2015). We recommend that soils be viewed in a One Health approach that recognizes that soil health goals include important ecosystem services including plant production, water regulation and purification, human health and climate regulation (Lehmann et al. 2020).

A One Health perspective positions soil health as central to agroecosystem sustainability and allows it to utilize shared metrics proposed by other working groups, from active carbon to ways to measure the economic and social benefit of healthy soil. Our (food) systems (sustainability) framework (Figure 1) has similarity to a community capitals framework (Flora et al. 2005). Another common theme of soil health and other working groups is terroir, and more broadly the Vermont brand. Small- and medium-sized farms in Vermont have unique attributes of both, but are also relevant due to farm size, as small farms feed 83% of the world's people (FAO 2016). Vermont farmers need 1) access to resources to better utilize their soil due to smaller size, 2) resiliency (beyond yield potential) to tolerate extreme weather with reduced inputs, and 3) an opportunity to pass the farm on within families (stewardship ethic).

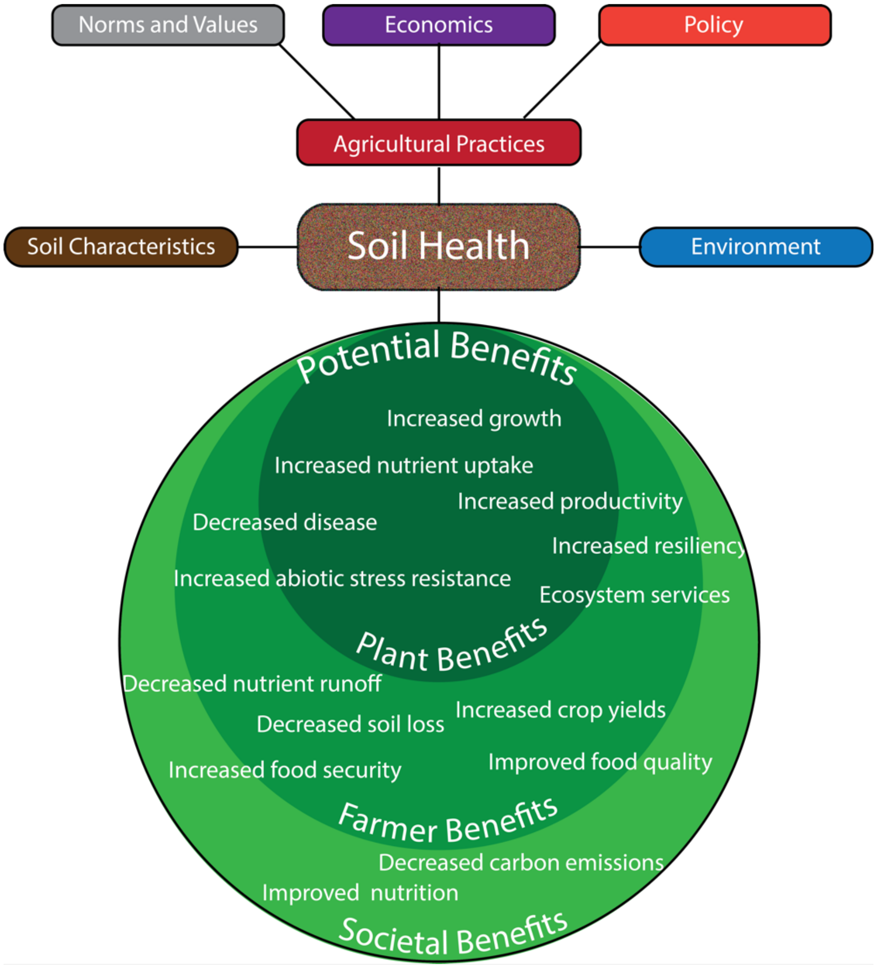

Figure 1. Soil health is impacted directly by agricultural practices, soil characteristics, and the environment. Potential benefits (green) to plants, farmers, and society depend on healthy soil. Agricultural practices reflect norms and values, economics, and policy. We propose a research center that encompasses all these different aspects with metrics to assess iterations and the resulting benefits.

III. Method

Previous research suggests that indicators should be selected in partnership with end users to achieve significant and sustainable improvements to soil health management (Bagnall et. al, 2020). In keeping with past findings, our team intentionally engaged multiple stakeholder groups throughout the process of identifying soil health metrics for Vermont farms.

We began the stakeholder engagement process by identifying key stakeholders in the state whose work is directly or indirectly tied to agricultural soil health. The initial list of stakeholders included farmers, researchers, extension agents and other agricultural service providers, policy experts, non-profit organizations, and state agencies. Members of our research team contacted key stakeholders and invited them to a virtual information session in mid-October. The information session included an overview of the new collaboration between ARS and UVM, the background of the research team, and the proposed outputs of the project. When communicating the overarching goal of our project, we used neutral language to avoid influencing stakeholders' existing perceptions of soil health and preferences for certain metrics.

On the same day that we convened the information session, we also launched an online survey to gather stakeholder perspectives on multiple dimensions of soil health, including their assessment of possible monitoring metrics. The IRB-approved survey was designed collaboratively by the research team and trialed by farmers and researchers. After incorporating feedback, we shared the survey with our original list of key stakeholders. We employed snowball sampling methodology (Morgan 2008) by requesting that key stakeholders share the survey within their Vermont-based networks; we specified that respondents must live and work in the state and that their work must be directly or indirectly tied to agricultural soil health in Vermont. The survey was administered via the Qualtrics platform, and results were completely anonymous. We collected responses from October through December 2020.

In mid-November, when our survey had been in the field for a month, we convened another virtual event to engage stakeholders in our research process. This event was shared more widely and with the larger networks of our original key stakeholders. At this event, we presented initial results from the survey. To contextualize these results and generate deeper conversation on soil health in Vermont, we also invited a panel of speakers to present their perspective on important factors relevant to monitoring, managing, and legislating for soil health. Our panelists included two farmers, two UVM Extension research professors, and two agricultural policy experts. Following the survey results and panel presentations, we facilitated a virtual dialogue with all attendees to identify the issues related to soil health that are most important and relevant to the broader Vermont agricultural community.

Throughout Fall 2020, our team worked internally and collaboratively to identify soil health metrics that are indicators of ecosystem service supply. Following the second stakeholder engagement event in November, we began an iterative process of integrating survey results with our internal concept map to identify soil health metrics that are both powerful scientific indicators of agroecosystem functioning and relevant and applicable for Vermont farmers. The internal and stakeholder events culminated in a conceptual diagram to examine flows, pools, and feedback loops of economic, environmental and social outcomes from local to global (Figure 1).

IV. Results and Implications

Between October and December 2020, we received 59 survey responses across the full range of relevant stakeholders (Figure 2). An overwhelming majority of respondents indicated that soil health was important for small- and medium-sized farms (86%), and that it should be a top priority for UVM research and outreach (91%).

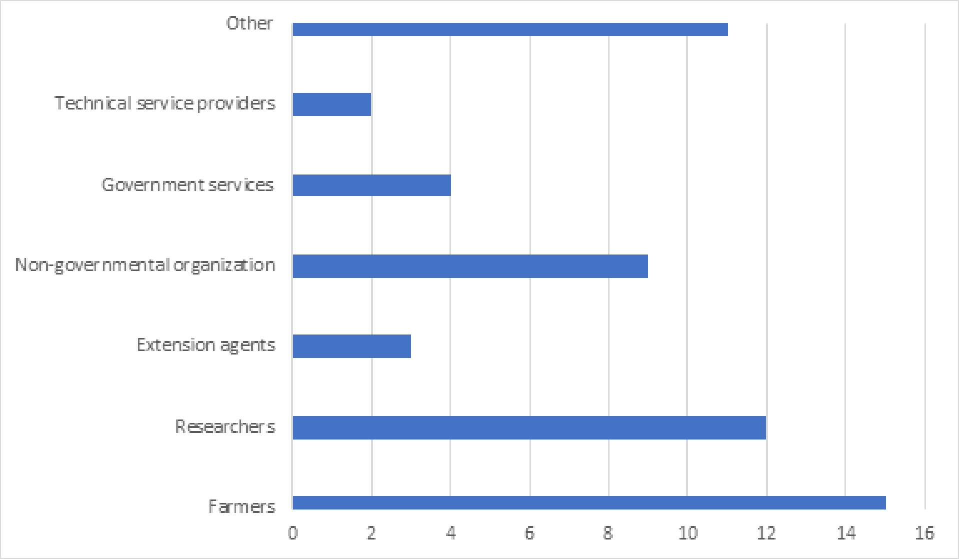

Figure 2. Survey responses organized by main stakeholder categories.

Survey respondents identified the following metrics as 'extremely important' for assessing soil health on Vermont's small- and medium-sized farms: organic matter (69% of respondents), beneficial microbes (62%), food web complexity (62%), aggregate stability (54%), active carbon (48%) and water infiltration (48%).

The metrics most frequently identified as 'extremely useful' for informing farmers' management decisions were organic matter (66% of respondents), water infiltration (50%), aggregate stability (47%), nitrogen availability to crops (45%) and bulk density (43%). The metrics most frequently identified as 'extremely useful' for informing soil health policies were organic matter (60% of respondents), water infiltration (57%), contaminants and toxins (45%), aggregate stability (38%) and phosphorus test levels (38%). These proportions reveal that there is less agreement regarding the utility of metrics for making policy than the utility of metrics for on-farm management decisions (Figure 3).

The future research and outreach priorities identified as 'extremely important' were long-term effects of management practices on soil health (80% of respondents), interactions between soil health and water quality (71%), and interactions between soil health and climate (66%). Due to an error with early survey administration, there were fewer responses to this question of future priorities (*n* = 32).

To contextualize Likert-scale responses, we asked respondents to describe how they assess soil health in their own words. Two major themes that emerged from this open-ended question were observational cues and the use of plant and crop health as important indicators of soil health. Specifically, respondents repeatedly reported observing soil physical structure to assess soil health. Respondents identified tilth, aggregate formation and size, and compaction as observations used to assess soil structure. Additionally, respondents repeatedly mentioned observing how water flows through their system as an observational indicator of soil physical structure. In terms of aboveground indicators, respondents mentioned plant health and vigor, plant diversity, crop productivity and biomass, and the number of growing days as indicators of soil health. Many respondents also mentioned observing life belowground as indicators of soil biology.

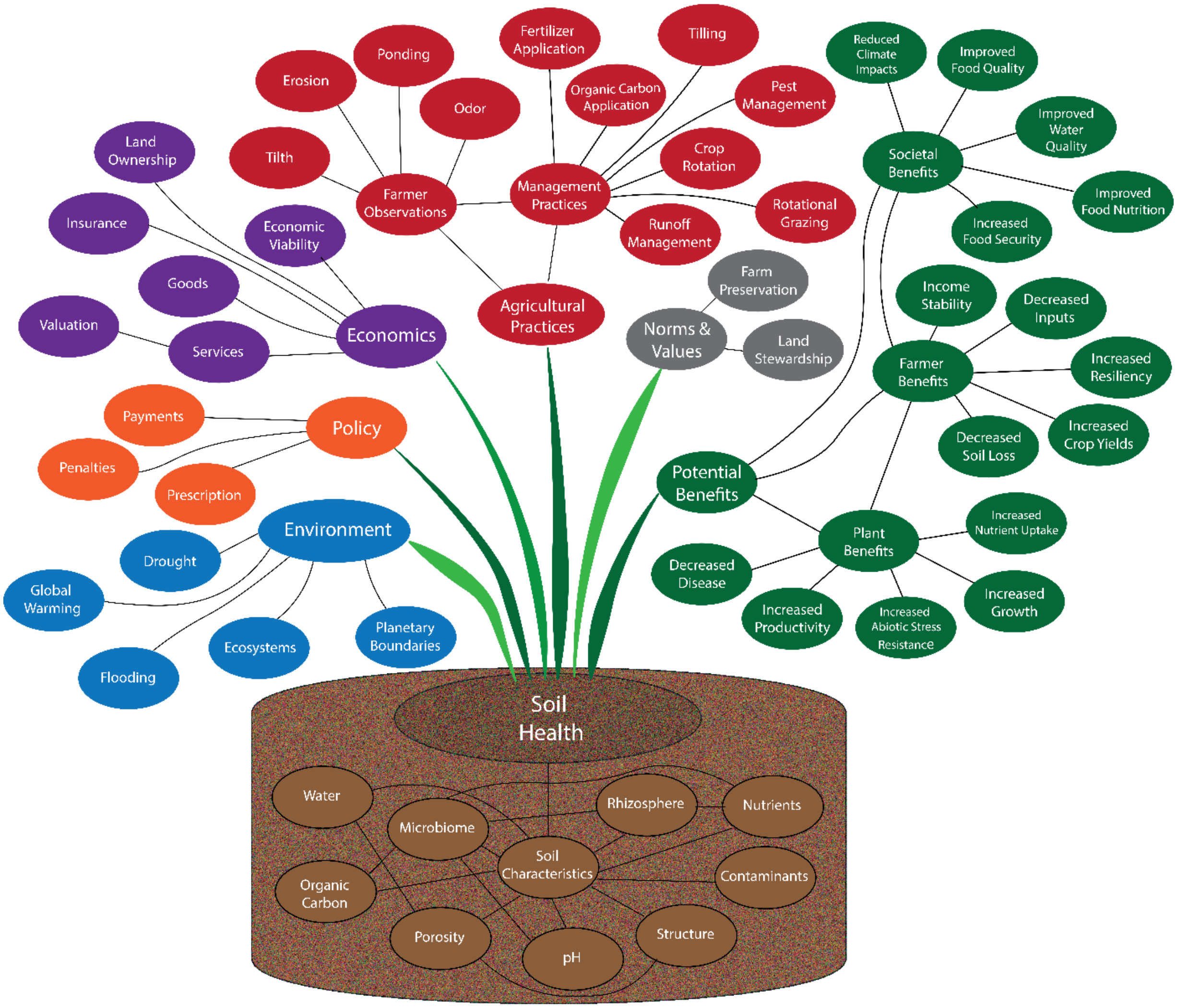

Figure 3. Conceptual map of nodes and connections related to soil health. As depicted in Figure 1, soil health is linked to soil characteristics (brown nodes), environment (blue), policy (orange), economics (purple), agricultural practices (red), and norms and values (grey). The potential benefits (green) of soil health are also shown. For simplicity, not all connections are depicted. Improved understanding of the strength and nature of connections between nodes can inform strategies to improve soil health and increase the benefits to plants, farmers, and society.

Understanding the economic and environmental benefits that healthy soil on Vermont farms could impart to our state is of direct interest to farmers, researchers and policy makers in the state of Vermont (Figure 3). Our team engaged multiple stakeholders invested in the state of soil health on farms in Vermont to develop our recommendations because they are the end users of indicators. We used the results from the stakeholder survey to guide us to the metrics deemed most useful for farmers (Table 2). Our team also identified soil health metrics that are indicators of ecosystem services supply, which have relevance to new state and federal policy (Vermont 2019 Act 83 – Soil Conservation Practice and Payment for Ecosystem Services, and

Federal s.3894 - Growing Climate Solutions Act of 2020). Specifically, these policy directives seek to compensate farmers for farm management that sequesters carbon, increases farm resilience to climate change, increases foundational soil health, increases storm water storage and mitigates agricultural runoff to surface waters. Tracking the contributions of small and medium sized farms in Vermont to these ecosystem services requires wider monitoring of established indicators, and the development of new metrics (Table 2B).

Our team recommends using the most benefit-relevant indicators possible-- metrics that capture the connection between ecological change and socially relevant outcomes (Olander et al. 2018). The supply and demand for ecosystem services from farms is influenced by agroecosystem management that impacts underlying ecological processes (Power 2011). Indicators of ecosystem service performance from agriculture should be both easily measured and sensitive to changes in the system (Dale and Polasky 2007).

Table 2. Soil metrics that are indicators of ecosystem function, relative utility to farm management decisions†, and whether they are available to farmers in Vermont.

Indicator/Metric	**Ecosystem Function(s)**	**Available soil tests with metric (price)**
Aggregate stability †	Reduces erosion, improves water infiltration, adds resilience to climate change impacts <u>Integrator</u>: physical structure & biology	CASH ($70-130 as part of test package), Woodward (=Haney)
Bulk density †	Decreased bulk density allows for improved water, air, and root growth, adds resilience to climate change impacts <u>Integrator</u>: physical structure, organic matter <u>Limitation</u>: simple measure but challenging to get an accurate sample and requires specialized equipment	UVM ($25)
Available water capacity	Amount of plant available water the soil can store	CASH ($70-130 as part of test package)
Nutrient (N, P) availability†	Contributor to crop yield, but excess decreases water quality	UVM, Haney, Solvita (~$25)
Active carbon (permanganate oxidizable carbon) (Culman et al. 2006)	Portion of soil carbon sensitive to management, reduces stormwater damage, resilience to climate change <u>Integrator</u>: SOM, aggregate stability & respiration	CASH ($70-130 as part of test package)
Soil organic matter (SOM) content†	plant and animal material that is decomposing, acts like a sponge to retain water and nutrients <u>Limitation</u>: combustion methods do not differentiate microplastics from SOM (Rillig 2018), unable to distinguish different pools of carbon	CASH, UVM ($70-130 as part of test package, ~15$ for test alone at UVM)

Soil respiration	Metabolic activity of soil microbial populations, associated with residence time of organic matter Limitation: insensitive to composition or function	CASH, Haney ($70-130 as part of CASH test package; direct measurements require ~$40,000 Infrared gas analyzer)
Bacterial and fungal biomass, trophic groups of protists, nematodes, and select soilborne pathogen genera	Biological buffering, nutrient cycling, plant productivity Limitation: insensitive to composition or function	Earthfort (~$80-150)
B. Priority measures currently unavailable to farmers		**Limitation / Impediment**
Plant health	Plant growth	Level of technology, and accuracy of method varies widely amongst farms
Dissolved and particulate nutrients lost in runoff and/or drainage	Nutrient cycling, water quality Integrator: nutrients, erosion, bulk density	Requires edge of field water monitoring or new technology (>$100)
Runoff volume/Water infiltration[†]	Landscape level measure of climate resilience Integrator: water holding capacity, bulk density, SOM	Requires edge of field water monitoring or new technology (>$100) Requires hours in relatively impermeable soils
Composition and function of soil food web (microbes and microinvertebrates)	Nutrient cycling, disease suppression, plant growth promotion	Requires specialists, metagenomics, and/or new technology (>$200)
Crop Yield	Food provisioning	Requires farmer survey or other data source (measured as part of harvest) Landscape scale requires remote sensing
Average net income and income stability	Direct measure of crop profitability, economic resilience of farming, cultural ecosystem services	Requires farmer survey or other data source (based on farmer bookkeeping)

Many universities and private facilities offer routine soil tests which typically cover chemical aspects of soil fertility (pH, phosphorus, potassium, micronutrients, cation exchange capacity (CEC)), and organic matter, averaging $15. Cornell University and several private laboratories offer soil health test packages ranging from $49.50-$130.00, depending on the institution and number of metrics tested (Table 2). Basic packages include nitrogen, other macronutrients, micronutrients, organic matter, active carbon, total carbon, and a soil health score. More involved packages include results for inorganic nitrogen, organic nitrogen, inorganic phosphorus, organic phosphorus, soluble salts, soil respiration, soil proteins, wet aggregate stability, available water capacity, compaction interpretation, texture, heavy metals, and a soil health score. Currently, Cornell University offers the most comprehensive assessment of soil health (CASH) including soil indicators for biological, chemical, and physical health (Schindelbick et al. 2016) and is the basis for many NRCS programs. Other labs (Earthfort, Woodward Labs) largely focus on biological indicators. Nonetheless, there are only six labs in the U.S. that publicly offer some type of soil health indicator in addition to soil chemical analysis. Only Cornell offers a comprehensive test that includes a soil health score and research-based recommendations to improve individual indicators and overall soils. As the focus on soil health and regenerative agriculture continues to grow, the demand for analysis by landowners may overwhelm the limited analytical capacity.

Vermont farmers are sending thousands of soil samples out of state for analysis each year. Vermont is the only state in the northeast that requires by law for farms to soil test their fields on a prescribed basis. This is missed revenue and jobs within Vermont. We have created environmental law but have not provided a research-based framework to truly help farmers keep their farms viable while protecting the environment. New USDA federal programs and state initiatives are focused on soil health with funds and support ready to go to farmers to understand soil health and implement changes to make improvements. UVM is positioned to be a regional leader in soil health research and outreach via new research, networks and partnerships linking soil health and ecosystem services (Table 3). However, samples and data for these projects are being outsourced to the Cornell CASH test, because we do not have infrastructural support to offer public testing services. There is a critical need for a UVM lab conducting the most relevant soil health analyses. Ideally, we can position ourselves to not only perform existing soil health analyses, but also develop and deploy low-cost sensors and lab-on-a-chip methods. In the same vein, we must invest in Extension to share knowledge and interpretation with the small and medium farmers who will most benefit from it.

Despite the inclusion of soil health metrics, existing soil health testing packages are far from comprehensive, and barely address beneficial microbes or micro-invertebrates. At best, they provide measures of biomass, general activity and trophic groups but not the composition (whether pathogenic or beneficial) or their ecological function(s) which require specialists and evolving technologies. Fortunately, we have expert scientists at UVM engaged in technology development (Table 3). However, none of the UVM faculty have funding to perform soil health measurements for farmers beyond targeted and grant-funded research.

Table 3. Knowledge capital available at UVM that focuses on research but no infrastructural support to offer public testing services.

Metric	Existing expertise
Active carbon (permanganate oxidizable carbon)	Roy (RSENR)
Soil organic matter (SOM)	Roy (RSENR), Faulkner (CALS)
Nutrients	Roy (RSENR), Faulkner (CALS)
Transcriptomics needed for functional genes (Fierer et al. 2021)	Scarborough (CEMS), von Wettberg (CALS)
Invertebrate composition	Neher (CALS), Gorres (CALS)
bulk density	Faulkner (CALS), Roy (RSENR), Darby (CALS), Gorres (CALS)
plant health	Harris (CALS), Neher (CALS),
plant available water	Neher (CALS)
water infiltration	Darby (CALS), Faulkner (CALS), Roy (RSENR)
Low-cost sensor networks for near- or real-time assessment on plot, farm and landscape scales (lab-on-a-chip)	Badireddy (CEMS)

Prepared manuscripts for peer-reviewed publications

1. Perspectives on soil health for small- and medium-sized farms, targeted for *Phytobiomes* (lead: Jeanne Harris)
2. Economics of soil health on small to medium farms during times of unpredictable change, targeted toward *Sustainability* (lead: Joshua Farley)

How to store/document and track data

There is a great need for improvements in data access and sharing for soil health. Traditionally most soil tests were private, between a farmer and an extension agent or state experiment station or commercial laboratory. There are good reasons for some privacy, as soil measurements can impact the value of a farm. However, data access policies established by NCBI/ENSMBL nearly four decades ago facilitated rapid developments in genetics, from medicine to agriculture. Likewise, public soil databases could facilitate similar developments, providing an invaluable baseline. One of our chief recommendations is that we must build and contribute to such databases, with proper protections of privacy as in medical genomics. This will allow all those working on soil health to build upon each other's contributions and facilitate the types of discoveries that can only be made from datasets larger than those a single investigator can build.

We are unaware of any large open-access soil datasets which assess comprehensive indicators of soil health. Data for national and state soil survey maps are largely public, but these do not reflect regular sampling or the impacts of ongoing farmer management of soils. Some of the larger soil testing groups, either at large state universities or in the private sector, have already built large, but private datasets. The Cornell CASH test has been deployed widely across the Northeast and been used by Cornell researchers for datamining (e.g., Fine et al. 2017). University-specific datasets are great for internal researchers, but the lack of data openness hinders the capacity of the outside research community, as well as small and medium-sized farm operators themselves, to make further use of the data.

Data sharing frameworks developed for DNA sequencing approaches may prove useful to archive estimates of food web function and microbial community structure based on culture-free sequencing approaches. The NCBI already has the capacity to preserve and make accessible sequences from environmental collections. Emerging from efforts to characterize whole communities, the GEOME project (Deck et al. 2017) has developed improved ways to harness metadata associated with environmental samples, to preserve the information on location of collection, ecological context, etc. that is needed to better utilize sequences contributed to GenBank.

With the advent of cheaper computing and next generation DNA sequencing, datasets across the biological sciences have grown in number and size, particularly in the past 15 years. Based on this trend, it has become clear that data openness and sharing is greatly aided by the development of trait ontologies. Trait ontologies can ensure that different groups are measuring the same thing, but the development of soil ontologies has not proceeded in parallel, making reproducibility a challenge. Although there are standard practices for a range of soil chemical and physical properties, these are largely lacking for biological characteristics. We think that the development of soil biological community ontologies is as important as making data open, as it is essential for comparing across datasets.

Challenges

We see multiple challenges for assuring the optimal provision of soil health in terms of social and ecological benefits. Specifically, we find challenges associated with measurements of soil organic matter and biology, spatial-temporal scaling, exclusion of soil health from economic assessments, and data accessibility. Furthermore, we face emerging challenges, in new pollutants (PFAS and antibiotic resistant genes), invasive species (e.g., earthworms, emerging crop diseases) and existing problems (nutrient overload and P pollution). Each challenge needs new, more effective solutions.

Measuring changes in soil organic matter is not trivial and requires long-term studies that leverage existing and emerging measurement tools. New spectral methods for measuring soil organic C concentration and stocks are rapidly becoming available. Spectral methods may eventually supply a cost-effective way to check soil organic carbon at several farms across Vermont. Another method that could prove useful for monitoring soil carbon cycling across multiple farms is active soil carbon (i.e., permanganate oxidizable carbon or POXC), which quantifies labile soil carbon rapidly and inexpensively (Culman et al. 2012). Compared with other soil carbon measures, POXC has greater sensitivity to changes in management or environmental variation (Culman et al. 2012). Models can also be used to estimate carbon cycling in agricultural systems as well. While models can be used to estimate fluxes or pools that are difficult to directly measure across many farms, it is important to calibrate models before use and evaluate the correlation between modeled and measured carbon fluxes and pools. As markets soil carbon mature, these models will be critically important.

Because biological assessments of soil health, in particular measurements of microbial and invertebrate communities, are relatively new and rarely used, their effect on plant health is often still unknown. For example, we need to understand how different agricultural practices can nurture or disrupt different communities and how different soil communities affect the health of plants before we can provide useful advice to farmers. Using microbes to improve crop productivity and soil health, as well as increasing resistance to environmental stress and plant disease, is attractive because of the ease of application, the potential for customization for different crops and sites and potential long-term benefits of improved soil health (Ray et al. 2020, Zhang et al. 2021). To customize our advice to Vermont farmers cultivating different crops on different soils in different geographical settings, we need to monitor soil communities, plant health and farmer management practices to understand those linkages and determine what practices can help cultivate specific microbial communities to support robust plant health and crop yield.

We hope that the emergence of new types of sensors will allow capturing of soil health data at a relatively fine scale, with multiple sensors placed in a single field, and perhaps capture different information such as soil properties (e.g., moisture, nutrients, pH), pollutants or the presence of different soil microbiomes and their role in ecosystem function. With sensors measuring data continually, researchers will not only be able to capture information on a much finer scale spatially, but also temporally. This increase in granularity will make it possible to improve our understanding of different agricultural practices or environmental effects on soil nutrients, organisms and water. Sensors constructed to report data regularly via wireless technology will allow researchers to capture data from many sites and many farms simultaneously, saving the labor of individuals to collect samples or measurements in the field and making it possible to have a larger-scale view across the state. Such a comprehensive data set would be a valuable resource for researchers and farmers. Within the past two years, we have been constructing and studying low-cost microsensors (~$3 per sensor electrode and $45 for overall sensor architecture), enabled by nanotechnology and advanced manufacturing technologies, for *in situ* soil nutrient and pollutant monitoring. With further funding, we could develop and test our low-cost sensors for field-scale high-resolution and high frequency monitoring of soil health parameters.

Another challenge is that markets send flawed, often perverse signals concerning the agricultural and ecological benefits of soil health. Agriculture accounts for less than 1% of US GDP, yet no economic activity is more important. The reason for this is that demand for food responds weakly to price, but price responds sharply to changes in supply induced by bad weather, pests, or other calamities. As a result, ag sector revenue and contribution to GDP paradoxically increase as output declines, though for a single farm, income increases with output. Furthermore, markets weight demand by income, forcing the poor and underfed to reduce food consumption by more than the rich when prices rise, so that in a highly unequal economy, markets allocate food to those who need it least. On the supply side, when farmers produce too little, prices skyrocket and the poor go hungry; when they produce too much, prices plunge, and farmers go bankrupt. Farmers increase production in response to rising prices, which should drive prices back down, but the season-long time-lag for output to respond weakens this negative feedback loop. Finally, many of the ecological benefits of soil health, such as carbon sequestration and water regulation, are off-site public goods and largely ignored by private markets. Policies designed to address these issues must be tailored to local socio-ecological systems and informed by interdisciplinary research integrating bio-geo-physical and socio-economic metrics (Farley et al., forthcoming).

Finally, as the number and sophistication of tests grows, it is important to provide farmers with actionable information, without overwhelming them by the amount of information. Besides its comprehensive nature, the CASH has been effective at giving farmers or other users actionable advice. Conversely, much information is not available publicly. Although an individual grower only needs information on management of their land, open data sources are key to bringing new analytical approaches to our shared challenges in a research community. The private nature of most soil test data is a hurdle we hope our efforts can help rectify.

V. Future Implications / Develop recommendations and pathways

Global perspective

Scaling is a big issue for both soil ecology (e.g., predators smaller than prey) and economics. We need tools and approaches to integrate processes required for monitoring and evaluating ecosystem services on various scales, from the rhizosphere to fields and farms, and on to the landscape. Microbiome sampling is increasingly powerful and will give improved indications of soil community resilience for farmers as we transition from measures of microbial taxa number to food web complexity. GIS and remote sensing tools increasingly can allow us to extrapolate from fields with known management to larger areas. If coupled with experimental work that indicates how agronomic management impacts microbial communities and nutrient mass balance of different crops, our power to extrapolate from research farms will improve. As new approaches such as rapid spectroscopy and digital mapping techniques mature, we will be able to distinguish various soil constraints and properties at plot, farm and landscape scales. But for these approaches to be most powerful across scales, we need frameworks for data openness and sharing so that make scaling possible.

Owing to the inelastic demand for food, the economics of soil health is particularly sensitive to scale. A small decrease in global food supply can drive dramatic increase in price, in response to which food becomes unaffordable to the poor leading to surges in malnutrition. This means that a relatively minor increase in crop yields resulting from improved soil health, or a minor decrease in yield variations from extreme weather events, can have significant impacts on global food security and economic stability. In contrast, over-production can cause prices to plunge, threatening the economic viability of farming (Farley et al. 2015). The ability to improve soil health may also be sensitive to farm scale. Ecological agriculture requires "a high ratio of eyes to acres" (Jackson and Berry 2009), which is the domain of small and medium size farms. In distinct contrast, large industrial farms rely on generic technological packages generated by multinational corporations and major research universities with little attention paid to local ecologies or social goals.

There is widespread agreement in the scientific community that producers and policymakers should take steps to not only eliminate further losses, but increase soil organic carbon on degraded agricultural lands (e.g., Amelung et al. 2020) both to reduce atmospheric CO_2 and to improve soil health. However, the global potential of soil carbon sequestration in working agricultural lands specifically is contested within the peer-reviewed literature, with some experts doubting that significant net greenhouse gas reduction benefits are possible due to numerous inherent trade-offs (Poulton et al. 2018; Rumpel et al. 2020). But even if sequestering soil carbon cannot solve climate change, it increases water and nutrient retention (Lal 2014) and promotes a healthier soil microbiome (Montgomery and Bickle 2016), which not only improves crop yields, especially during years with extreme weather, but also improves ecological outcomes (Capellesso et al. 2015). More research is needed to clarify the benefits and costs of increasing soil organic carbon on Vermont's agricultural lands and elsewhere in the US, along with the related benefits for overall soil health and farmers. This work will require interdisciplinary collaboration that spans soil science, agronomy, biogeochemistry, microbiology, modeling, life cycle assessment, and economics.

Vermont perspective

The Vermont Agency of Vermont requires nutrient management plans (NMPs) of farmers and mandates they evaluate soil test levels every three to five years depending on farm size. Recently, the USDA NRCS updated their NMP standard and now requires soil tests to be no older than two years old upon plan development. Vermont makes policy decisions from research done 30 years ago at UVM to evaluate agricultural systems that have since evolved. Soil science used to be a strength in CALS at UVM but has been lost due to attrition over the past 20 years. Other colleges have partially filled the void with soil-related hires, so the expertise is scattered across campus (Table 3) and not directly linked to small- and medium-sized farms. It is time to update those guidelines for Vermont policy and in support of our farmers and mainstay of agriculture and protection of the environment in the state. Given the breadth of environmental regulation in the state of Vermont, one would assume UVM is providing extensive scientific data to support farmers and to support regulatory frameworks to meet the needs of food production and environmental protection. By capturing the dollars outflowing to neighboring states' labs (NY, ME), we could create jobs and serve our state by adding a dedicated soil scientist and staff person to process samples here in VT.

In terms of agricultural policy, there is an ongoing struggle to ensure agricultural output is high enough to keep consumer prices low, yet not so high that food prices crash, threatening farm viability. Past agricultural policies sought primarily to balance these objectives through controls on commodity prices and production, both of which focus on large farms and tend to promote over-production (Winders 2009), reducing the viability of small and medium farmers not eligible for the subsidies with significant impacts on small rural states such as Vermont. Expanding the focus of agricultural policy to include soil health and ecological benefits could improve these outcomes (Angelo 2010). State or national payment for ecosystem service programs to promote soil health, currently under consideration in Vermont, could compensate farmers for improving soil health, with evolving private carbon/ecosystem service markets such as IndigoAg (indigoag.com) and Working Lands (working-lands.com) playing a complementary role, thus diversifying farmer income streams. Faced with over-production, policies could favor investments in long term soil health over short term yields; faced with a food shortage, policies could favor greater output. Small farmers with more intimate knowledge of their land (more eyes to acres) likely have a comparative advantage when it comes to improving soil health. Over time, improved soil health should help stabilize yields in the face of climate change and extreme weather events. By adopting such policies before the rest of the country, Vermont could potentially have more stable yields than elsewhere, leading to windfall profits for individual Vermont farmers when low yields elsewhere drive-up agricultural prices, while simultaneously helping to stabilize food supplies to the benefit of the food insecure (Farley et al., forthcoming).

We have a unique opportunity to nurture the groundswell of interest in learning and practicing soil health in Vermont. We propose an iterative engagement between researchers and stakeholders to establish a mechanism that serves the public good. Extension can provide leadership in this role and will benefit from the range of expertise in soil health on main campus.

Key takeaways and recommendations for ARS planners

- Biological elements of soil health are underrepresented in soil health programs but are of interest to Vermont farmers, are challenging to measure, but optimizing soil biology has the potential to have a strong impact on plant growth and tolerance to abiotic and biotic stress.
- Soil organic matter is also of interest to Vermont farmers as a key component of soil health, but there are measurement challenges, as well as outstanding research. questions related to trade-offs involved in efforts to boost soil organic carbon on farms.
- Soil health testing packages exist but should be improved, and at a time when increased interest and research in soil health is growing, this is an opportunity for UVM. Data access and sharing from testing is limited, hindering the capacity of researchers to build on past data collection.
- Vermont farmers are engaged in environmental conservation and soil health improvements; hence we have a willing audience.

- Vermont has strict regulatory policies that also require improvements on farms that impact soil health.
- The scale of Vermont and agricultural landscape as well as the willingness to participate make it a perfect fit to highlight what can really be done to maximize soil health and realize the outcomes of doing such. We can be a model to other states.

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