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Holistic systems thinking underpins Vermont soil health practitioners' preferences and beliefs

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ABSTRACT

The concept of soil health has potential to catalyze agricultural transformation, though the breadth of the concept may stifle action. The impact of the soil health concept on practice depends on how well the concept is understood by diverse agricultural practitioners, including farmers, extension, and researchers. We use two surveys of soil health practitioners, or those that manage or influence soil, to examine soil health preferences and beliefs. Both surveys are from Vermont, USA, a region consisting mostly of small-to-medium scale farms: survey one queried Vermont soil health practitioners in the fall of 2020 ($n = 62$) and survey two queried just Vermont farmers in the spring of 2022 ($n = 179$). Analysis included qualitative coding and statistical analyses, including *t*-tests, ANOVA and information theory-informed regression analysis. In study one, Vermont practitioners' definitions include the holistic dimensions of soil health as a living ecosystem, the underlying conditions for life to thrive, the production of ecosystem services, and enhancing resilience. Additionally, practitioners rate biological, chemical, and physical indicators as very useful and important, and these ratings do not, in general, vary between decision contexts. In study two, Vermont farmers perceive the benefits of soil health. The importance of soil health is best predicted by beliefs in climate change. Together these studies suggest that in Vermont, the concept of soil health is aligned with systems-oriented thinking about resilient agricultural systems. We conclude that systems thinking is an important factor for improving soil health and practice adoption.

1. Introduction

Healthy soils are critical to sustainable agricultural production. Improvements in soil health have been associated with increased productivity, decreased need for chemical inputs, decreased environmental harms such as nutrient runoff, decreased farm system vulnerability to extreme weather patterns under climate change, and increased carbon sequestration, which aids in global climate change mitigation (Chaparro et al., 2012; Doran et al., 1996; Lal, 2016). Soil health as a concept has broad applicability across farm, regional, and global scales and thus can serve as a foundation to develop shared goals and visions among farmers, scientists, policy makers, and public citizens (Lehmann et al., 2020). This "versatility" of the concept of soil health also creates opportunities for multiple interpretations, a proliferation of measurement approaches, and divergent perspectives on "good" soil health between stakeholder groups (Janzen et al., 2021; Lehmann et al., 2020). In

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practice, what soil health means, how to measure it, and what measurements mean for soil assessment, farm management decisions, and broader soil and agricultural policy decisions continue to be questions of interest (Heinz Center, 2008; Janzen et al., 2021; Stewart et al., 2018). Here, we acknowledge ambiguity in the use of the term soil health and use it to refer to both a state that can be measured using chemical, biological and physical metrics and a concept leveraged to guide management decisions towards long-term sustainability (Lehmann et al., 2020). The broader concept of soil security, which positions threats to soil as a global challenge on the scale of food and water security, among others, recognizes that the way society and land managers relate to and understand soil is core to its protection (McBratney et al., 2014). This is particularly relevant as public and private investment in soil health continues to grow (Basche et al., 2020; Karlen et al., 2017). The extent to which soil health can and is mobilizing agriculture towards more sustainable, climate-adaptive, and resilient systems depends on how soil health practitioners (SHPs)—those that manage or influence soil, including farmers, extension, and agricultural researchers—understand the concept (Baveye, 2021; Billings et al., 2021; Heinz Center, 2008; Lehmann et al., 2020). In this study, we use two surveys of SHPs from Vermont, USA to examine soil health preferences and beliefs.

The concept of soil health evolved from the concept of soil quality to explicitly emphasize soil biology as comprising a living meta organism and soil interactions more broadly with the environment and people (Lehman et al., 2015; Lehmann et al., 2020; Neher et al., 2022). The increasing focus on soil health and the role of living microorganisms within soils can be seen as a response to a historical overreliance on chemical and physical indicators for soil management that has undermined biological functioning and thus contributed to soil degradation (Neher et al., 2021). Researchers initially defined soil health as “the continued capacity of the soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health” (Doran et al., 1996, p. 11). While soil health is a more holistic concept than soil quality, SHPs’ interpretation of the concept varies across a spectrum from a holistic property emergent from complex relationships to a reductionist catalog of measurements (Kibblewhite et al., 2007; Mann et al., 2021). At its core, the concept relies upon the metaphor of “health”, which “implies – almost *demands* – an ecological systems perspective” (Janzen et al., 2021, p. 4 emphasis in original). Yet, recent debate revived the question of whether the concept of soil health is too vague and intrinsically unmeasurable to provide meaningful inputs for improving outcomes or is a useful boundary-spanning concept that can mobilize a cross-scale sustainability transformation in agriculture (Baveye, 2021; Harris et al., 2022; Janzen et al., 2021; Lehmann et al., 2020; Powlson, 2021).

Farmers, extension agents, soil scientists, and others, who we collectively refer to as SHPs, rely on a broad range of indicators to assess soil health. Most soil health assessments reflect the qualities of a site’s soils with respect to (1) biological (e.g., microbial biomass, soil respiration rate), (2) chemical (e.g., soil organic matter & carbon, pH, nutrient availability), and (3) physical (e.g., infiltration rate, bulk density, soil aggregate stability) properties (Doran et al., 1996). There have been efforts to produce a standardized set of indicators since the early 1990s (National Research Council, Committee on Long-Range Soil and Water Conservation Policy, 1993), but standardized indicators are yet to be adopted on a broad scale. Therefore, studies have varied widely in their selection of soil health indicators. This has led to lack of clarity about the relationships between soil health interventions (e.g., cover cropping, no tillage) and outcomes and difficulties calibrating results to local conditions (Caudle et al., 2020; Roper et al., 2017; Stewart et al., 2018). The diversity of available soil health tests and disagreement as to what values indicate healthy soils, similarly reflect this challenge; what one test deems “healthy” in relation to a specific metric might be rated as “unhealthy” in another testing program (Hughes et al., 2023). Likewise, SHPs’ perceptions of, and preferences for, indicators are diverse. For example, farmers often describe their soils’ health using perception-based indicators like smell, color, perceived ease of tilling, and estimated rates of debris decomposition (Harris and Bezdicek, 1994; Romig et al., 1995). Recently, there has been a shift towards more mixed qualitative and quantitative assessments, with farmers incorporating feedback from quantitative tests into management (Bagnall et al., 2020). In addition, farmers frequently use crop yield and biomass as indicators of soil health (Andrews et al., 2003; Bagnall et al., 2020).

Improvements in soil health on farms require understanding the concept, belief in and motivation to improve soil health, and management actions. However, “understanding *what makes people care*” about soil is an underexplored dimension of soil security (Pozza and Field, 2020, emphasis in original). Soil health beliefs underpin potential actions, advice, and decisions by SHPs, including the adoption of soil health practices (Carlisle, 2016; Prokopy et al., 2019). Previous research found that farmers with a soil stewardship ethic used reinforcing feedback from conservation practice adoption, observation, and assessment to further stewardship efforts (Roesch-McNally et al., 2018). Notably, most USA-based research on soil health beliefs, soil stewardship ethics, and practice adoption has been within the midwestern Corn Belt, though it is likely that there are variations in beliefs and ethics between agroecological regions. Therefore, understanding farmers’ soil health beliefs and what factors influence and predict them can help bridge gaps between soil health goals and actions (Roesch-McNally et al., 2018).

In the present work, we use two surveys from Vermont, USA, a region where agriculture is dominated by small- and medium-scale farming operations, to explore practitioners’ preferred methods for defining and measuring soil health and to identify how and to whom soil health matters. Specifically, we ask: (1) How do Vermont SHPs conceptualize soil health? (2) What are their preferred methods for assessing soil health across decision contexts? (3) How important is soil health to Vermont farmers? And finally, (4) What types of Vermont farmers think soil health is important? Our results point to Vermont SHPs’ holistic understanding of soil health as emergent from the complex relationships of multiple indices and suggests that systems thinking is an important underlying factor for implementing practices.

2. Materials and methods

2.1. *Vermont Soil Health Metrics Preferences survey (study 1)*

From October through December 2020, we used the Vermont Soil Health Metrics Preferences survey to collect data on SHPs’ soil health definitions, assessment methods, and preferred metrics for different decision contexts using the online Qualtrics survey platform (Neher et al., 2021). We used snowball sampling of key contacts and statewide listservs to recruit a convenience sample of Vermont practitioners working towards improved soil health on farms to capture the breadth of ways in which the concept is understood in the field. As such, we aimed to recruit a diversity of respondents that interact with soil in their professions, including farmers, extension agents, soil scientists, and others. The survey instrument included both open-ended response questions and closed Likert scale questions. To assess SHPs’ perceptions of soil health metrics, a suite of 12 metrics, including chemical, physical, and biological indicators, were selected. Following the best practices recommended by Bagnall et al. (2020), researchers selected soil metrics based on prior engagement with relevant stakeholders (Neher et al., 2021), resulting in a final list of metrics included in the online survey (Table 1). The survey instrument was approved by the University of Vermont Institutional Review Board.

2.1.1. *Qualitative analysis*

The survey instrument included the following open-ended response questions: 1. What does healthy soil mean to you? 2. What is/are the main way(s) that you assess soil health? Vermont SHPs’ responses to these questions were analyzed via an inductive, *in-vivo* coding approach

Table 1
List of soil health metrics considered in the Vermont soil health practitioner soil health metrics survey (study 1).

Indictor	Category	Ecosystem Function(s)
Active Carbon	Chemical	Portion of soil carbon sensitive to management, resilience to climate change
Aggregate Stability	Physical & Biological	Reduces erosion, improves water infiltration, adds resilience to climate change impacts
Beneficial Microbes	Biological	Biological buffering, nutrient cycling, plant productivity
Bulk Density	Physical	Decreased bulk density allows for improved water, air, and root growth, adds resilience to climate change impacts
Contaminants & Toxins	Chemical	Plant productivity, health and safety for biology and humans
Disease-Causing Microbes	Biological	Plant productivity
Food Web Complexity	Biological	Nutrient cycling, disease suppression, plant growth promotion
Nitrogen Availability	Chemical	Nutrient cycling, water quality
Organic Matter	Biological, Physical, & Chemical	Plant and animal material that is decomposing, acts like a sponge to retain water and nutrients
Phosphorus	Chemical	Nutrient cycling, water quality
Soil pH	Chemical	Nutrient cycling, soil toxicity
Water infiltration	Physical	Reduces erosion, mitigates extreme rain impacts at landscape level (measure of climate resilience)

(Saldaña, 2015). For each question, one member of the research team analyzed the response text to create the preliminary emergent coding framework. The inductive coding for soil health meaning focused on the nature of the relationship between the respondent and soil. The initial coding framework resulted in 3 codes: living ecosystems, conditions for life to thrive, and produces ecosystem services. The inductive coding for the soil health assessment methods focused on identifying emergent categories of methods. The initial coding framework resulted in 5 codes: specific metrics, soil testing, production and yield, sensory perception, and observation. This preliminary framework for both questions was then given to a second member of the research team to apply. After the second coder applied the codebook, the emergent codes were compared with the literature on soil health definitions (Janzen et al., 2021; Lehmann et al., 2020) and it was decided to add a fourth code, resilience, to the soil health meaning and combine two codes, observation and sensory perception in the assessment categories, resulting in four codes each. With the revised codebook, each coder then applied the framework independently and results were compared using Cohen's Kappa for interrater reliability demonstrating moderate agreement for meaning ($k = 0.59$) and substantial agreement for assessment ($k = 0.69$) (McHugh, 2012). Discrepancies between the coding were reconciled through discussion between the two coders to determine the most applicable codes.

2.1.2. Quantitative analysis

The survey instrument asked Vermont SHPs to rate the level of usefulness or importance of the 12 soil health metrics under three different decision contexts: 1) how important are the following metrics for assessing soil health on small- and medium-sized farms in Vermont? (*assess*), 2) how useful are the following metrics for informing management decisions related to soil health on small- and medium-sized farms in Vermont? (*manage*), and 3) how useful are the following metrics for informing public policy related to soil health on Vermont farms? (*policy*).

The focus on small- and medium-sized farms in these questions reflects the research team's interest in understanding the unique barriers and opportunities for improving soil health for these sizes of farms, the predominant farm sizes in Vermont, as described more fully in Neher et al. (2021, 2022). Responses to these questions were on five-point (*assess*) or seven-point (*manage* and *policy*) Likert scales. In R Statistical Software (R Core Team, 2024), the responses were transformed into a numeric scale and then standardized with larger values representing higher ratings. Each question also included an "I'm not sure" option, which was removed from the statistical analysis (Supplementary Material Table S1). We examined the mean response for each of the 12 metrics in Table 1 for the *assess, manage*, and *policy* questions.

The standardized responses were grouped into two SHPs types—"farmer" and "non-farmer"—to examine differences in support for indicators. Farmers ($n = 17$) comprised the "farmer" group and all other stakeholder groups (researchers, extension agents, policymakers, etc.) were combined into a single "non-farmer" group ($n = 48$). Respondents who wrote their own responses to questions instead of selecting one of the pre-written stakeholder categories were excluded from this analysis. We performed two-tailed *t*-tests to analyze the difference in mean response scores between the farmers and non-farmers for each metric within each question (e.g., "active carbon" within *assess*). To be conservative in our interpretation of the results, we applied a Bonferroni correction to account for multiple hypothesis testing, which shifted the cutoff for significance from 0.05 to 0.001 (Lee and Lee, 2018).

Additionally, we compared differences in support for indicators between different soil health decision contexts using analyses of variance (ANOVA) and Tukey's post-hoc tests (Pituch and Stevens, 2015). We included only respondents who responded to all three questions for a given metric. Soil health metrics with significant differences between scores in the different decision contexts (i.e., an ANOVA p-value < 0.004 applying the Bonferroni correction) were then subjected to Tukey's ad-hoc test to examine pair-wise differences.

2.2. Vermont Farmer and Conservation and Payment for Ecosystem Services Survey (study 2)

We collected data from Vermont farmers between February and April 2022 on farmers' soil health beliefs, stewardship motivations, farm demographics, and experience with soil testing using the Vermont Farmer and Conservation and Payment for Ecosystem Services Survey (White, 2022). The instrument was developed via a multi-phase process: we received input from the Vermont Payment for Ecosystem Services Working Group, Vermont farmers, UVM researchers, UVM extension staff, and non-profit advisors, then the instrument was reviewed with a focus group of 12 farmers in January 2022, and finally it was trialed by five farmers. The survey instrument was approved by the UVM Institutional Review Board. Vermont farmer participants were recruited via farmer networks and with the assistance of organizations involved in the Vermont Payment for Ecosystem Services Working Group. Participants took the survey both through an online survey hosted by Qualtrics and over the phone with UVM staff.

2.2.1. Quantitative analysis

To assess Vermont farmers' soil health beliefs, participants were asked the degree to which they agreed with four statements regarding soil health on a four-point scale from disagree to agree: (1) improvements in soil health have many benefits for my farm, (2) improvements in soil health on my farm will have benefits for the environment outside of my farm, (3) changes on my farm can have a big impact on soil health, and (4) farmers should take additional steps beyond required practices to protect soil health. To identify potential predictors of these soil health beliefs, we drew from theoretical and applied literature. Drawing on value-norm-belief theory (Stern et al., 1999), we included environmental stewardship motivations and farm financial motivations to explore if these values underpin soil health beliefs. Drawing from the soil stewardship ethic concept developed by Roesch McNally et al. (2018), we explored vulnerability to environmental impacts, vulnerability to erosion, climate change beliefs, and financial and knowledge capacity as predictors of soil health beliefs. Finally, drawing from empirical work on conservation adoption, we included farm size, soil texture, education, experience on the farm, gender, whether the respondent is from a historically socially disadvantaged group, and whether the farm is organic (Carlisle, 2016; Prokopy et al., 2019) to explore how these factors vary with soil health beliefs. This resulted in 20 potential variables of interest (Tables 2, 3). The data was cleaned and analyzed in R Statistical Software (R Core Team, 2024).

To reduce the number of variables considered in the analysis, three preliminary groups of variables were identified as potential indices from the correlation matrix (Supplementary Fig. S1): soil health importance beliefs, climate change beliefs, and experience with soil testing. The three groupings of variables demonstrated high internal consistency with a Cronbach's alpha close to or higher than the generally accepted 0.7 cutoff (Table 3) (Nunnally, 1978). We then created new index variables from each of the groupings through exploratory factor analyses, which further confirmed that each index had a single dimension via the scree and parallel process method (DeVellis and Thorpe, 2021).

With a modest sample size and large pool of potential predictors, we took an Information Theory approach (Burnham and Anderson, 2002) to identify variables predictive of soil health beliefs. The Information Theory approach relies on running many potential linear regression models (with and without variables of interest) and then compares models based on their Akaike Information Criteria (AIC) scores, a measure of model fit. We ran model simulations for every combination of the 15 independent variables against the dependent variable, the constructed soil health importance index, resulting in over 32,000 potential models. The top twenty-five best-fitting models (i.e., within 2 AIC points) were identified and combined via a model averaging approach (following methods by Naidoo et al., 2011).

3. Results

3.1. Vermont SHPs' conceptions of soil health

The final sample for the Vermont Soil Health Preferences Survey consisted of 62 participants, including farmers ($n = 17$), researchers ($n = 13$), non-governmental organization employees ($n = 9$), government service providers ($n = 5$), extension agents ($n = 3$), technical service providers ($n = 2$) and others ($n = 13$), as the latter including "gardener/arborist", "writer and educator about soil health", etc. (Supplementary Fig. S2).

In response to the question, "What does healthy soil mean to you?", our process of inductive coding identified four categories within Vermont SHPs' responses: (1) living ecosystem, (2) conditions for life to thrive, (3) produces ecosystem services, and (4) resilience (Table 4). These categories were not mutually exclusive but reflect distinct dimensions of soil health mentioned by respondents. Two-thirds of the respondents ($n = 41$, 66 %) mentioned more than one category, and three respondents mentioned all four (Supplementary Table S2).

The most mentioned category was conditions for life to thrive. This category represents the properties of soil health, including the physical and chemical properties, that facilitate life growing and living in the soil. One respondent mentioned, "Healthy soil is an essential basis for all life on earth. It is soil that has high organic matter, the ability to sequester carbon, ability to filter and retain water, and does not have nutrient losses." Definitions in this category all referenced soil a critical foundation for life. The second most mentioned category was living ecosystem, which focused on the biological components of soil health, or the living micro- and macro-organisms within soil, and in some cases surpassed that to reflect on a "soil organism" itself. One respondent mentioned, "Healthy soil is active with diverse life forms including fungi, bacteria, and other microorganisms; invertebrates; animals; and plants/plant roots." More than providing the conditions for life, this category reflects soil as being alive and filled with biological activity. The third most mentioned category was produces ecosystem services,

Table 2
Descriptive statistics of variables included in the Information Theoretic regression analysis predicting Vermont farmer stated importance of soil health (study 2).

Variable name	Survey question	N	Distribution
Farm size	How many acres do you farm?	179	1 (1–9 acres): 22.35 %; 2 (10–49 acres): 20.67 %3 (50–179 acres): 18.44 %4 (180–499 acres): 23.46 %5 (500–999 acres): 10.61 %6 (1000–1999 acres): 1.68 %7 (2000+ acres): 2.79 %
BIPOC	Do you identify as a Black, Indigenous, or other Person of Color?	147	0 (No): 90.48 %1 (Yes): 9.52 %
Financial capacity	I have the financial capacity to enhance soil health on my farm	147	1 (Disagree): 9.52 %2 (Somewhat disagree): 33.33 %3 (Somewhat agree): 41.50 %4 (Agree): 15.65 %
Knowledge capacity	I have the knowledge and technical skill to enhance soil health on my farm	147	1 (Disagree): 1.36 %2 (Somewhat disagree): 8.16 %3 (Somewhat agree): 61.22 %4 (Agree): 29.25 %
Environmental stewardship motivation	Primary motivations for implementing conservation practices, as ranked by farmers – Stewardship of the environment off your farm (water quality, soil health, ecosystem health, wildlife/plant biodiversity)	151	0 (Unranked): 26.49 %1 (3rd strongest motivator): 17.88 %2 (2nd strongest motivator): 34.44 %3 (1st strongest motivator): 21.19 %
Financial motivation	Primary motivations for implementing conservation practices, as ranked by farmers – Financial (farm viability, economics, long-term cost savings)	151	0 (Unranked): 56.29 %1 (3rd strongest motivator): 14.57 %2 (2nd strongest motivator): 10.60 %3 (1st strongest motivator): 18.54 %
Education	Level of education	147	1 (High school or equivalent): 8.84 %2 (Some college coursework completed): 8.84 %3 (Technical or occupational certificate OR associate's degree): 16.33 %4 (Bachelor's degree): 40.82 %5 (Master's degree): 22.45 %6 (Doctorate): 2.72 %
Farming experience	Years of farming experience	146	Mean: 21.12 Median: 15 Standard deviation: 16.01
Gender	Gender	147	0 (Female OR Non-binary): 46.94 %1 (Male): 53.06 %
Organic	Is any part of your farm under organic certification?	178	0 (No): 57.30 %1 (Yes): 42.70 %%
Soil Texture	How would you describe the most common soil texture on your farm?	178	1 (Sand): 3.93 %2 (Sandy-loam): 17.42

(continued on next page)

Table 2 (*continued*)

Variable name	Survey question	N	Distribution
			%3 (Silt): 2.81 %4 (Silty-loam): 18.54 %5 (Loam): 25.84 %6 (Clay-loam): 19.10 %7 (Clay): 12.36 %
Vulnerability to environmental impacts	Perceived vulnerability – extreme weather events in recent years have affected my long-term management goals	147	1 (Disagree): 7.48 %2 (Somewhat disagree): 14.97 %3: (Somewhat agree): 44.22 %4: (Agree): 33.33 %
Vulnerability to erosion	Perceived vulnerability – at least some of my land has experienced significant soil erosion in the last five years	147	1 (Disagree): 36.73 %2 (Somewhat disagree): 22.45 %3: (Somewhat agree): 26.53 %4: (Agree): 14.29 %

Table 3
Constructed indices included in the analysis, including component question statements that are combined to create the index, the Cronbach's alpha for internal reliability, and results of an exploratory factor analysis to determine dimensionality of the index (study 2). All indices have one factor solutions via the scree plot extraction method and only one eigenvalue greater than zero. The soil health importance index is the dependent variable in the regression analysis in study 2.

Index Name	Component Question Statements	Cronbach's Alpha	Number of Factors	Eigenvalues (>1)
Soil health importance	Improved soil health benefits my farm Improved soil health benefits the environment Changes on my farm can impact soil health Farmers should do more to protect soil health	0.72	1	2.25
Climate change beliefs	Climate change is caused by human activities We are in a climate emergency due to climate change I have a responsibility to be a part of climate solutions	0.93	1	2.64
Experience with soil testing	Test aggregate stability Test bulk density Test emissions Test organic matter	0.69	1	2.07

which focused on the benefits that healthy soils provide for people, including water quality, climate change mitigation, food production, and others. One respondent mentioned, "Soil that serves the ecosystem to keep it healthy. Water quality, climate mitigation, food and fiber production, medicines, are all dimensions of this". Definitions included in this category emphasized a more human-centered focus of what soil does for us. Finally, the last and least mentioned category was resilience. This category focused on the ability of healthy soils to withstand external impacts and recover quickly. For example, one respondent wrote, "Healthy soil has a high percentage of organic matter, is biologically active and diverse, has a high-water holding capacity, and is resilient to pest and disease pressures." Most in this category specifically used the word "resilient" or "resilience".

Table 4
Categories of participants' description or definition of soil health, definitions of the categories, and frequency of mentions of the category by the full sample, just farmers, and other SHPs (study 1).

Soil Health Meaning Categories	Definition	Total Mentions *n* = 62(%)	Farmer Mentions *n* = 17(%)	Other SHPs Mentions *n* = 45(%)
Living Ecosystem	Soil as alive or a component of soil health is active biology, or diverse microbes, etc.	35 (56 %)	9 (53 %)	26 (58 %)
Conditions for Life to Thrive	Traits of soil health, framed as "Supporting" life and ecosystems.	45 (73 %)	11 (65 %)	34 (76 %)
Provides Ecosystem Services	Benefits and outcomes of soil health, including water quality, carbon sequestration, food production, etc.	29 (47 %)	7 (42 %)	22 (49 %)
Resilience	Soil's ability to provide or enhance an on-farm resilience against a variety of external pressures, such as climate change and biological or chemical threats.	8 (13 %)	0 (0 %)	8 (18 %)

In response to the question, "What is/are the main way(s) that you assess soil health?", our analysis identified four categories within Vermont SHPs' responses: (1) specific soil health metrics (2) lab-based soil testing, (3) direct observation, and (4) crop production and yield (Table 5). Again, these categories are not mutually exclusive, and more than half of respondents (n = 34, 55 %) mentioned two or more categories, although none mentioned all four (Supplementary Tables S2 and S4). The most mentioned category was direct observation, which reflects mentions of observation of soils in the field (i.e., direct), including senses of touch, smell, and feel. One respondent mentioned, "as a farmer, I primarily assess soil health by smell, texture, color, and general "feel" - i.e. intuition and observation!". The second most mentioned category was lab-based testing, which included any reference to soil health tests, or a testing facility and named lab-based tests. For example, one respondent specifically mentioned that they have "soil nutrient analyses processed by [the University]", whereas another more vaguely mentioned that they "do soil testing on a 3-year cycle." The third most frequently mentioned category was the mention of specific soil health metrics, which included references to named metrics (e.g., Table 1), such as aggregate stability and soil organic matter. Responses in this category used the named metrics to define their assessment methods. Finally, the least mentioned category was production and yield, which included any reference to quantity or yield of crop produced on a field. One respondent wrote that they assess soil health through "tracking crop production".

3.2. Preferred metrics for assessing soil health across decision contexts

Across decision contexts, Vermont SHPs' assessments of the twelve soil health metrics showed high importance and utility. For assessing soil health on small- to medium-sized farms, the mean scores for ratings of all twelve metrics were above 0.50 on a scale of zero to one, with zero representing "not at all important" and one representing "extremely important" (Fig. 1). For nine of the metrics, including water infiltration, organic matter, nitrogen availability, food web complexity,

Table 5
Categories of participants' description of their personal methods for assessing soil health, definitions of the categories, and frequency of mentions of the category by the full sample, just farmers, and other SHPs (study 1).

Methods for Assessing Soil Health Categories	Definition	Total Mentions *n* = 62(%)	Farmer Mentions *n* = 17(%)	Other SHPs Mentions *n* = 45(%)
Specific Soil Health Metrics	Metrics that are used alone or in combination, e.g., aggregate stability, bulk density, organic matter, percolation test, pH, presence/ absence of microbes/ nematodes, etc.	24 (39 %)	4 (24 %)	20 (44 %)
Lab-Based Soil Testing	The use of soil testing, either in a vague reference to soil testing or a specific soil health test or testing facility, e.g., Cornell Assessment of Soil Health (CASH) test, University of Vermont (UVM) testing, other reference to soil testing or lab-based tests.	26 (42 %)	8 (47 %)	18 (40 %)
Direct Observation	Visual observations of soil and/or use of senses, e.g., touch, smell, feel, look, including field observations of plant health	41 (66 %)	14 (82 %)	27 (60 %)
Crop Production & Yield	Quantity of crop production or yield	6 (10 %)	2 (11 %)	4 (9 %)

contaminants and toxins, bulk density, beneficial microbes and active carbon, the mean score was above 0.75.

For informing management decisions on small- to medium-sized farms, the mean scores of all twelve metrics on a scale of zero to one, with zero representing "extremely useless" and one representing "extremely useful", were above 0.75 (Fig. 2).

For informing policy decisions on Vermont farms, the mean scores of all twelve metrics on a scale of zero to one, with zero representing "extremely useless" and one representing "extremely useful", were above 0.75 (Fig. 3).

Comparing ratings for each metric across the three decision contexts, i.e., assess, manage and policy, revealed significant differences between contexts for two of the twelve metrics: nitrogen availability ($F = 8.27$, $p > 0.001$) and phosphorus ($F = 14.05$, $p > 0.001$) (Table 6). For nitrogen availability, respondents rated the metric as significantly more useful for management than assessing soil health and informing policy ($diff = 0.13$, $p < 0.001$; $diff = 0.08$, $p = 0.04$, respectively). For phosphorus, respondents rated the metric as significantly more useful for informing policy ($diff = 0.16$, $p < 0.001$) and management ($diff = 0.13$, $p < 0.001$) decisions than assessing soil health.

Comparing farmer and non-farmer respondent ratings of metrics within each decision context via *t*-tests revealed only one significant difference in metric ratings: farmers rated aggregate stability as more important for assessing soil health on farms than non-farmer respondents ($t = -3.51$, $p < 0.001$) (Fig. 4, Supplementary Table S5). The remaining *t*-tests comparing farmer to non-farmer respondents' ratings for assessing soil health on farms were non-significant, as were all 12 comparisons between farmer and non-farmer ratings for the manage and policy decision contexts (Supplementary Figs. S3 and S4).

3.3. *Vermont farmer belief in the importance of soil health*

A total of 179 Vermont farmers responded to the Vermont Farmer and Conservation and Payment for Ecosystem Services Survey. As a convenience sample, we compared farmer demographics with the 2022 USDA National Agricultural Census (National Agricultural Statistics Service, 2023) data for Vermont and found that the sample distribution differed from the broader Vermont population in a few important ways: the study 2 sample is over-representative of smaller (i.e., 1–9 acres) and larger (i.e., >500 acres) farms, there is a more diverse age range represented, and the sample is skewed towards higher grossing farms than the general Vermont farm population (Supplementary Table S6).

The Vermont farmers in the sample held strong soil health beliefs across the four statements used to assess importance of soil health beliefs (Fig. 5). All respondents either agreed ($n = 123$, 84 %) or somewhat agreed ($n = 24$, 16 %) that improvements in soil health have many benefits for their farms. The vast majority agreed ($n = 108$, 73 %) and somewhat agreed ($n = 36$, 24 %) that improvements in soil health on their farms will have benefits for the environment outside of their farms. Likewise, most respondents agreed ($n = 87$, 59 %) or somewhat agreed ($n = 55$, 37 %) that changes on farms can have a big impact on soil health. Finally, most respondents agreed ($n = 93$, 63 %) or somewhat agreed ($n = 47$, 36 %) that farmers should take additional steps beyond required practices to protect soil health.

3.4. *Predictors of vermont farmer soil health importance beliefs*

The Information Theory approach yielded a 25-model average, which included 12 variables: farm size, climate change index, environmental stewardship motivations, experience soil testing index, financial capacity, years of on-farm experience, vulnerability to environmental impacts, knowledge, gender, soil texture, education, and financial conservation motivations (Table 7). These 12 variables were selected from the pool of 15 via the Information Theoretic approach because they added explanatory power to the models as demonstrated in the AIC score associated with the top 25 models (Supplementary Table S7). Of these 12 variables, only climate change beliefs were found to be a significant and positive predictor of soil health importance beliefs ($\beta = 0.30$, $p < 0.001$).

4. Discussion

While soil health has been situated as an ideal concept to spur soil management approaches that are both ecologically and economically beneficial, the degree to which the concept is motivating this action remains contested (Baveye, 2021; Harris et al., 2022; Janzen et al., 2021; Lehmann et al., 2020; Powlson, 2021). The perspectives of SHPs' presented here help us understand the role of soil health as a motivating concept. The results from the two Vermont-based surveys point to Vermont SHPs' characterization of soil health as a holistic concept that is best understood through multiple means of assessment, aligning with the proposition that the concept is a boundary-spanning motivator (Janzen et al., 2021). We support this conclusion through the triangulation of the results from these two data sources, as well as the qualitative and quantitative approaches within them.

4.1. *Conceptualization of soil health*

The definitions and assessment methods of soil health highlighted by Vermont SHPs in these two studies align with an evolution of the concept towards a more holistic understanding of soils. The four categories we identified from the definitions of Vermont SHPs capture the

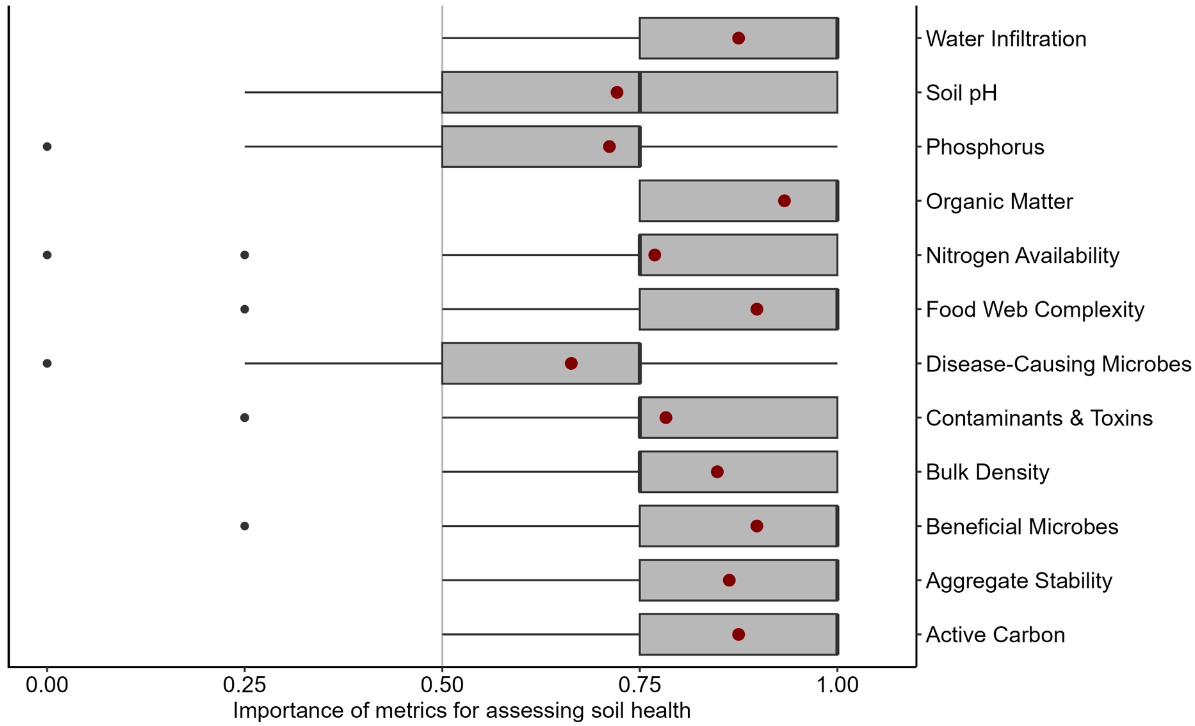

Fig. 1. Box plots of responses and mean score (red dot) for each soil health metric for importance for assessing soil health on small- and medium-sized farms in Vermont (study 1). Median score is represented by the thick black bar on the box.

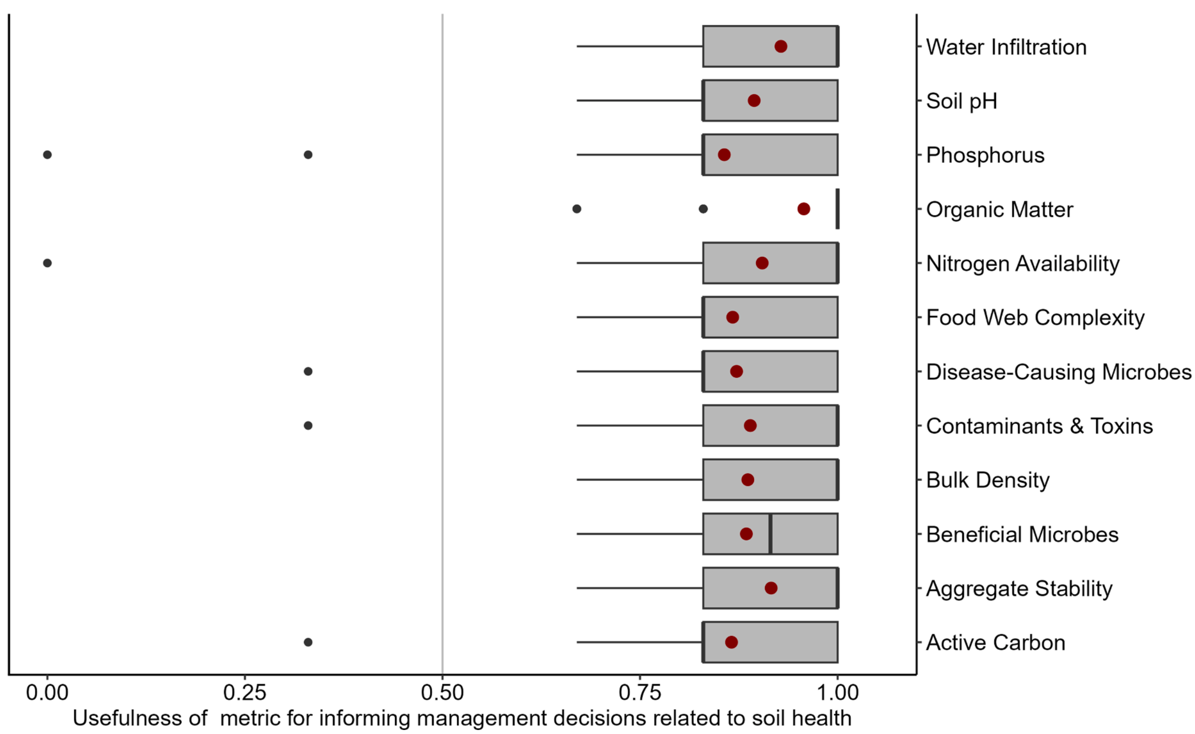

Fig. 2. Box plots of responses and mean score (red dot) for each soil health metric for usefulness in informing management decisions related to soil health on small- and medium-sized farms in Vermont (study 1). Median score is represented by the thick black bar on the box.

breadth of dimensions cited as comprising a holistic definition of soil health amongst different definitions in the literature. Additionally, these categories align with Janzen et al.'s (2021) three dimensions of soil health: functionality, which is the ability of the soil to perform its basic processes; vitality, representing soil as a living system; and sustainability or resilience, which is the long-term, persistent nature of these processes. Most respondents mentioned both "conditions for life to thrive" and "produce ecosystem services". Combined, these elements represent the dimension of functionality which includes "not just 'services', which intend to imply direct human benefit, but also processes that maintain integrity and stability of the biosphere beyond immediate human demands" (Janzen et al., 2021, p. 2). The category of "living

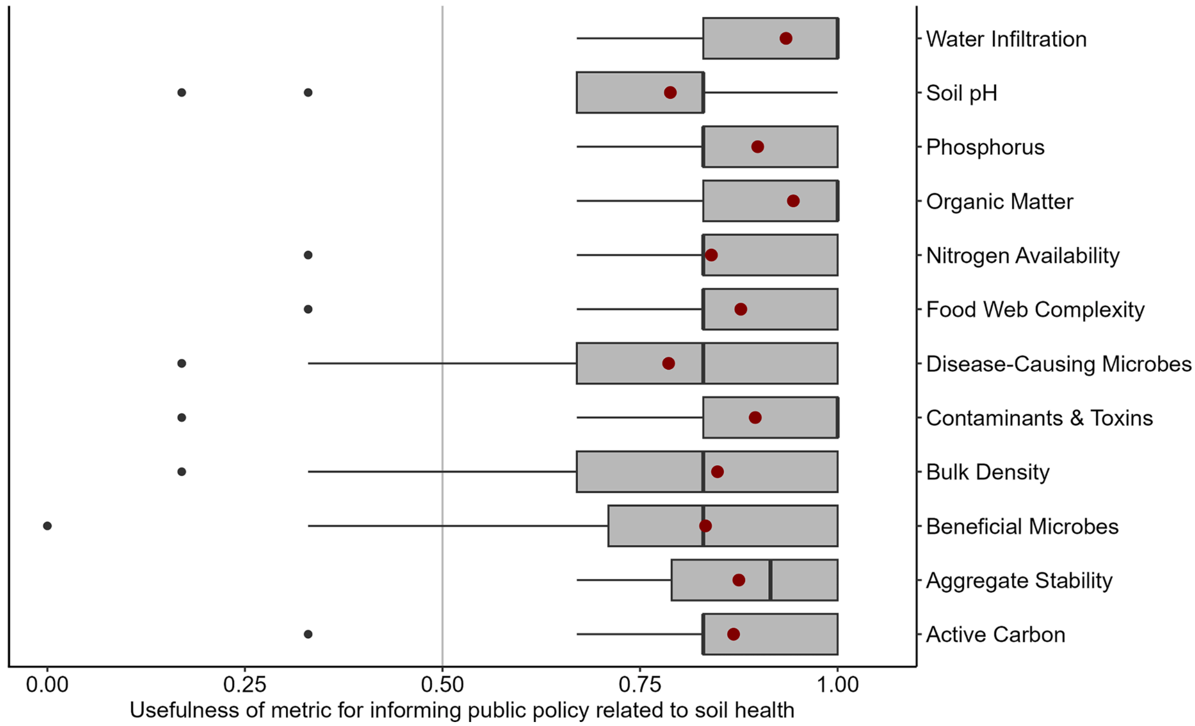

Fig. 3. Box plots of responses and mean score (red dot) for each soil health metric for usefulness in informing public policy related to soil health on Vermont farms (study 1). Median score is represented by the thick black bar on the box.

Table 6
Results of ANOVA and Tukey's ad-hoc tests conducted on metrics for differences between decision contexts (study 1). Metrics with a significant difference between the three groups, as determined by the ANOVA and a Bonferroni-corrected p-value of $p < 0.001$, also include the Tukey's post-hoc comparison between groups.

Soil health metric	F-value	ANOVA p-value	n	comparison	Tukey's difference	Tukey's p-value
Active Carbon	0.36	0.70	37	–	–	–
Aggregate Stability	2.31	0.10	42	–	–	–
Beneficial Microbes	1.33	0.27	38	–	–	–
Bulk Density	1.59	0.21	42	–	–	–
Contaminants & Toxins	4.18	0.02	39	–	–	–
Disease-Causing Microbes	5.29	0.01	34	–	–	–
Food Web Complexity	0.70	0.50	39	–	–	–
Nitrogen Availability	8.27	<0.001	41	policy - assess	0.05	0.24
				manage - assess	0.13	<0.001
				manage - policy	0.08	0.04
Organic Matter	0.30	0.74	46	–	–	–
Phosphorus	14.05	<0.001	41	policy - assess	0.16	<0.001
				manage - assess	0.13	<0.001
				manage - policy	−0.02	0.72
Soil pH	4.60	0.01	29	–	–	–
Water Infiltration	2.60	0.08	45	–	–	–

ecosystems" is also highly representative of the concept of vitality, which connotes life, energy, and the act of living. Finally, there is clear overlap between our category of "resilience" and Janzen et al.'s (2021) concept of sustainability or resilience. However, it is notable that this category had the least mentions across the group. Further research is needed to understand how resilience fits into Vermont SHPs' perceptions of soil health.

These categories similarly overlap the definitions found amongst Mann et al.'s (2021) study of Canadian maritime farmers' soil health perceptions through the emphasis on biological terms represented by the definitional category that identified healthy soil as living ecosystems. This was the second most prominent category mentioned by over half of respondents. Unlike the maritime farmers described in Mann et al. (2021), however, respondents in our Vermont sample did not focus on yield and production dimensions in defining soil health. The prominence of the emergent living ecosystem category suggests that the transition within the scientific community towards acknowledging the critical role of biological communities within soil health (see Lehman et al., 2015; Neher et al., 2021) is also reflected in the majority of Vermont SHPs surveyed. It is also important to note that over two-thirds of respondents mentioned more than one category in their definition of soil health. This multi-dimensional understanding is reflective of early work on the concept of soil health. Previous literature noted that "soil health is enhanced by management and land-use decisions that weigh the multiple functions of soil and is impaired by decisions which focus only on single functions" (Doran et al., 1996, p. 3).

4.2. *Assessment of soil health*

Complementing the breadth of the practitioners' definitions of soil health is the breadth of the assessment methods they relied on. Most Vermont SHPs mentioned a reliance on direct observations (qualitative

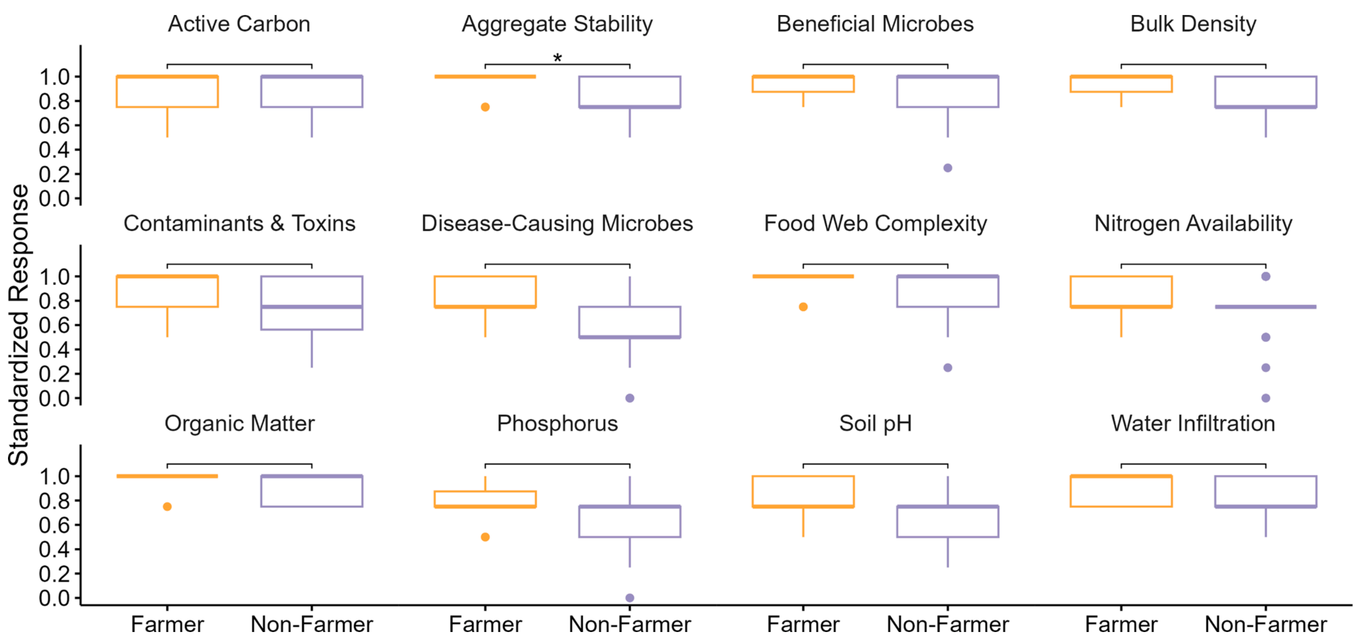

Fig. 4. Box plots comparing farmer and non-farmer stakeholder groups' response distribution for each soil health metric for the assess decision context (study 1). [*] indicates significance at the Bonferroni-corrected threshold of $p < 0.001$ level. Orange boxes represent the distribution of farmer responses. Purple boxes represent the distribution of non-farmer responses, such as by researchers, technical advisors, or policy makers.

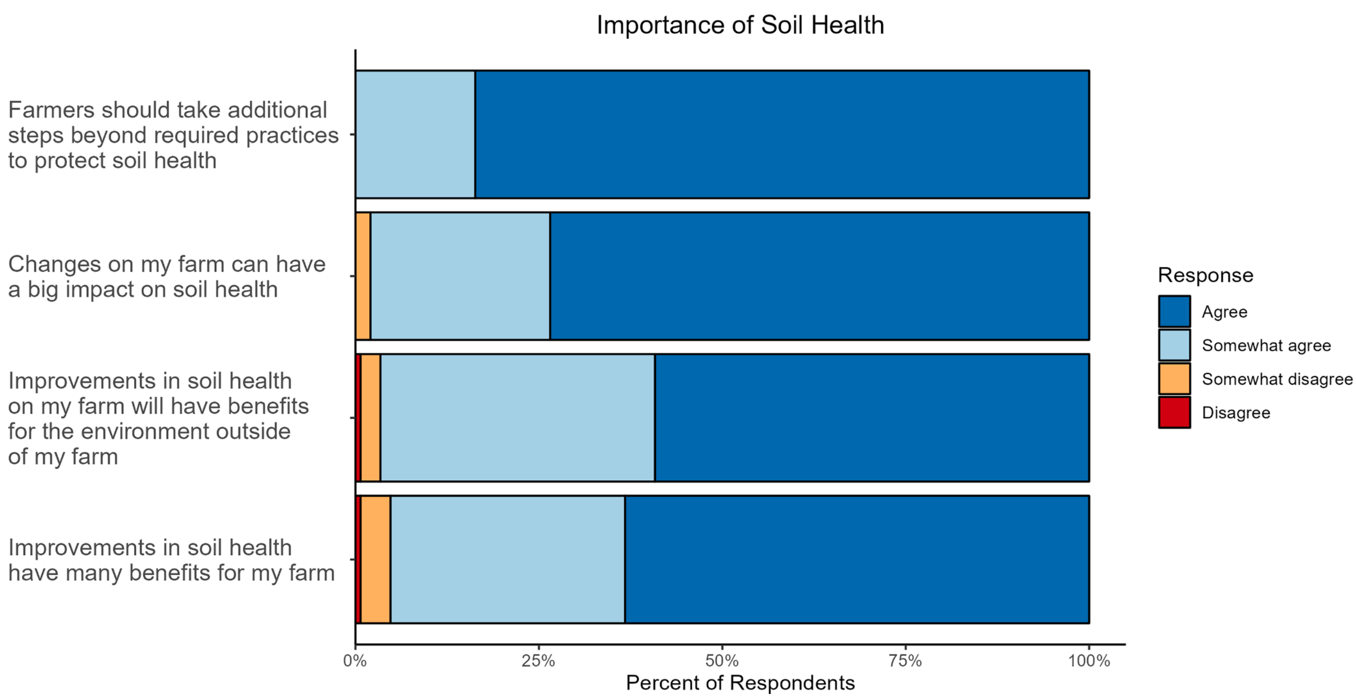

Fig. 5. Vermont farmer rates of agreement with four soil health belief statements on a scale of disagree to agree (study 2).

assessment), but a substantial portion also mentioned the use of specific tests (e.g., aggregate stability) and the use of lab-based soil tests (quantitative assessment), while a few respondents also used yield as a proxy for soil health. These results align with previous research that found practitioners rely on a mixture of quantitative tests and qualitative sensory observation to assess soil health (Bagnall et al., 2020). Many practitioners maintain a preference toward qualitative sensory observation, as evidenced by the prominence of direct observation, such as smell, texture, color and feel, in respondents' assessment methods (Romig et al., 1995). Still, when the categories of specific and lab-based tests are combined, a majority of respondents mention a reliance on quantitative tests. Interestingly, Wade et al. (2021), note that U.S.A. midwestern farmers found information on soil health tests to be of high value, but this did not translate into high levels of test use, which suggests farmers are interested in soil tests, but they face barriers to adoption. While we do not examine the adoption of tests in our study, our results align with findings from Wade et al. (2021) that farmers find information from soil health indicators to be highly useful. Finally, the preference for yield and biomass as a proxy for soil health was present, but much less prominent than the other categories. As such, we suggest that the conflation of soil health and yield that has been found previously may be less of an issue within our study region. Future research

Table 7
Twenty five-model averaged regression model predicting Vermont farmer soil health importance beliefs (study 2). Climate change beliefs are the only significant predictor of soil health beliefs in this averaged model. Three variables were dropped from the analysis in the averaged model through the Information Theoretic approach as they did not add variation to the models within 2 AICc points of the top model: BIPOC, organic, and vulnerability to erosion.

Independent Variables	Regression Coefficient (β)	SE	Adjusted SE	*p*-value
(Intercept)	−0.10	0.39	0.39	0.79
Farm size	−0.05	0.05	0.05	0.39
Climate change beliefs	0.30	0.08	0.08	<0.001
Environmental stewardship motivation	0.12	0.07	0.07	0.11
Experience with soil testing	0.15	0.10	0.10	0.11
Financial capacity	−0.04	0.07	0.07	0.60
Farming experience	0.00	0.00	0.00	0.89
Vulnerability to erosion	0.01	0.04	0.04	0.80
Knowledge capacity	0.03	0.07	0.07	0.71
Gender	−0.01	0.05	0.05	0.83
Soil texture	0.00	0.01	0.01	0.91
Education	0.00	0.02	0.02	0.87
Financial motivation	0.00	0.01	0.01	0.93

could investigate the degree to which this is representative of a broader trend.

When considering a set of 12 soil health indicators (inclusive of physical, chemical, and biological metrics shown in Table 1), on average Vermont SHPs rate all indicators as very useful and important. Our quantitative testing of practitioners' preferences found that indicator ratings do not vary among assessment, management, and policy decision contexts except for in two cases, with phosphorus and with nitrogen indicators. We suggest that the case of phosphorus is more likely due to Vermont political processes than a broader conceptualization of soil health. Respondents rated phosphorus as more useful for policy and management decisions than for assessing soil health on farms. In the past decade, the state of Vermont passed legislation to manage phosphorus runoff from farms via 'Required Agricultural Practices' due to water quality issues in various watersheds, most notably the Lake Champlain basin (Hammond Wagner et al., 2020). Thus, phosphorus levels are central to Vermont SHPs' policy and management decisions but may tell us less about the actual state of soil health (i.e. assessment). In the case of nitrogen, Vermont SHPs rated the metric more useful for management than assessment and policy. We suggest that this may reflect the importance of managing nitrogen as an input for crop production and that nitrogen levels were more salient to SHPs because of on-farm assessments and observations rather than external influences.

Overall, the high ratings of the suite of soil health metrics by Vermont SHPs align with Andrews et al.'s (2003, p. 187) insight that farmers found "it would be most useful to have access to several forms of the information." Furthermore, there was a very high level of agreement amongst those that were surveyed (i.e., almost no difference between the metric ratings of Vermont farmers and non-farmers in our sample). The only metric that differed significantly between these two groups was aggregate stability, which all farmers except one rated as extremely important compared to other practitioners' ratings, which were high but more variable. This displays the relatively undisputed importance of aggregate stability amongst respondents and its significant salience in the collective understanding of soil health. Of note is that physical, chemical, and biological metrics were all rated similarly highly by farmers and non-farmers in our sample. The use of biological metrics is evolving rapidly, and recent research has shown that farmers are interested in biological indicators from soil health tests but struggle to understand the associated data and implications for management (Lehman et al., 2015; Neher et al., 2021; Singh et al., 2024). While our results do not speak to the understanding of soil biological indicators, they do echo the interest in biological indicators.

In sum, the definitions and assessments of soil health offered by Vermont SHPs align with the reflection that "soil health offers potent, evocative meaning…but it cannot be squeezed into a single number without subjective, disputable value judgements" (Janzen et al., 2021, p. 5). As no single measure paints a full picture of the system, multiple measures offer unique insight to piece together into a more complete picture of soil health. Intervention strategies should reflect this preference for a diverse suite of metrics rather than focus on singular measurements.

4.3. Soil health beliefs

Vermont farmers hold strong soil health beliefs, and they are directly linked to beliefs on climate change. Of the four affirmative soil health belief statements presented to farmers, most farmers agreed or somewhat agreed with them. Beliefs in climate change are a strong predictor of Vermont farmer beliefs about soil health. Amongst the initial 15 variables included in the models on soil health beliefs and practice adoption and the resulting 12 variables in the averaged model, climate change beliefs were the only significant predictor of soil health importance beliefs. Previous research has linked both soil conservation behavior and climate change beliefs to holistic, systems-oriented thinking. A review of qualitative studies looking at conservation practice adoption in the USA identified a few studies where "thinking about and managing the farm as a system" was found to be motivate adoption (Ranjan et al., 2019, p. 1178). For example, Indiana farmers that adopted cover crops were more likely to be systems thinkers than those who had not adopted cover crops (Church et al., 2020). Regarding climate change beliefs among adults in the USA, systems thinking is a predictor of climate change risk perception and policy support (Lezak and Thibodeau, 2016). Systems thinking has also been related positively to beliefs about global warming (i.e., climate change), however this relationship, at least in the sample of adults in the USA, was found to be indirect: the positive link between systems thinking and climate change beliefs was mediated by an ecological worldview (Ballew et al., 2019). Systems thinking as a cognitive framework allows people to conceptualize the interconnections and feedbacks present in the world, thus enabling the development of an ecological ethic, defined as an ethic which we should care for and protect our world. This serves as the foundation for accepting and understanding climate change (Ballew et al., 2019). Of note in our study, both focal questions (soil health beliefs and climate change beliefs) are skewed very highly positive amongst the whole sample. This is likely a bias of our relatively small Vermont sample. In this preliminary exploration of soil health belief predictors, we suggest there may be a latent variable, either systems thinking and/or an ecological worldview, driving both soil health importance and climate change beliefs. The ability to conceptualize multiple, complex relationships and feedback loops, as opposed to reductionist thinking that partitions and narrows focus, appears to be an important foundation for soil health beliefs.

4.4. Holistic systems thinking and soil health preferences and beliefs

The results from these two Vermont-based studies point to SHPs' holistic understanding of soil health as emergent from the complex relationships of multiple soil properties and dimensions. In study 1, Vermont SHPs' definitions of soil health reflected a multi-dimensional concept that accounts for life within the soil, contributions beyond the soil, and a long-term resource (although the latter to a lesser extent). Additionally, both qualitative and quantitative data collected on assessment methods from study 1 point to near consensus on the use of multiple metrics across decision-making contexts. In study 2, we found climate change beliefs to be the sole significant predictor of soil health beliefs, which we suggest represents both an ecological ethic and a systems thinking perspective. The holistic, systems-oriented thinking about soil health that is reflected in both studies suggest that within our

Vermont-based sample the concept is aligned with systems-oriented thinking about sustainability, climate change adaptation, and resilient agricultural systems (Janzen et al., 2021; Lehmann et al., 2020; Powlson, 2021).

The holistic nature of the soil health concept has enabled its popularity and momentum across stakeholders and geographic scales (Lehmann et al., 2020), and our results suggest that this resonates with Vermont SHPs. Due to the cross-sectional nature of both datasets in this research, we cannot comment on the directionality of the relationship between holistic, systems thinking and soil health (i.e., whether systems thinking is an entry point to soil health for Vermont SHPs or if soil health is an entry point for systems thinking). We hypothesize that it is likely both, and there may be additional entry points to both concepts, including an ecological ethic. The linkage between soil health and systems thinking is important because they likely reinforce each other and may lead to behavior changes amongst practitioners. In particular, research with USA midwestern Corn Belt farmers suggest that observations of the social-ecological feedbacks via the impact of extreme weather events on farms, implementation of soil conservation practices, and observation of on-farm results (often in comparison to neighboring farms) contribute to the development of a soil stewardship ethic (Roesch-McNally et al., 2018). In another example in Texas, USA, researchers found that soil health was an important contributor to farmers' stewardship ethics for both adopters and non-adopters of soil health practices such as no-till (Bagnall et al., 2020). We hypothesize that a systems thinking or an ecological ethic latent variable exists and is driving both soil health beliefs and climate change beliefs results seen in study 2. Future research should investigate the relationship among systems thinking, ecological ethics, soil health beliefs, and adoption of soil health practices.

From a practical perspective, if we accept the holistic or systems-oriented nature of the concept, soil health researchers and practitioners are left with the question of how to make sense of the many indicators. If all indicators are important, what does this mean for the design of tests, metrics, and/or indices? Lehmann et al. (2020, p. 551) suggested using multi-approaches to make sense of metrics: multi-criteria decision analysis, inclusivity of farm- and regional-scale indicators, and dynamic and interactive metrics based on the question at hand (p. 551). While some might argue that this could dilute the effectiveness of soil health assessments, 'healthy' soils will always be context- and value-dependent (i.e., what is 'good' soil depends on who is asking and why). A standard set of indicators may alienate SHPs who do not see their system reflected in a measurement framework. Moreover, ambiguity can be an asset in driving towards transdisciplinary systems thinking; connecting researchers, practitioners, and the public; and driving creativity in research and practice (Janzen et al., 2021). Vermont SHPs strongly support the entire suite of metrics presented in study 1. Our results suggest that an integrated approach to measuring the emergent properties of soil health focusing on relationships, processes, and performance rather than reductionist measurements would potentially align more closely with SHPs' understanding of soil health, and therefore influence decision making (Harris et al., 2022; Kibblewhite et al., 2007). Given that soil health testing is practiced by a minority of farmers, estimated at 30 % of farmers in the USA (Lobry de Bruyn and Andrews, 2016), and that there is a persistent gap in the adoption of soil health practices amongst farmers in the United States (Carlisle, 2016; Prokopy et al., 2019), there is much work to be done to improve adoption of soil health testing practices. These results suggest that systems thinking is an important underlying factor for implementing soil health in practice. When focusing on indicators, we need to keep in mind that they are not the whole system, just the 'visible' parts of the system.

5. Conclusion

Improved soil health is associated with several important benefits for farms, including productivity, environmental benefits, and increased resilience (Chaparro et al., 2012; Doran et al., 1996; Lal, 2016). Its broad applicability across farm system types, geographic scales, and sectors has been framed as both an asset, with the ability to motivate transformation, and a detriment, in that ambiguity could stymie real change. The results from these two Vermont-based studies point to the resonance of the systems thinking-oriented of the soil health concept amongst Vermont SHPs. To support this, we draw four primary conclusions. First, Vermont SHPs define healthy soils as living ecological communities that support ecosystems and provide ecosystem services and draw on both quantitative and observational metrics for assessing soil health. This aligns with the evolution in thinking of soil health towards a more holistic understanding of soils. Second, Vermont SHPs on average rate a suite of 12 biological, chemical, and physical indicators tested as very useful and important. Third, these ratings do not vary among assessment, management, and policy decision contexts, except for with nitrogen and phosphorus indicators. In general, farmers rated indicators the same or higher than other SHPs. Fourth, climate change beliefs are a strong predictor of Vermont farmer soil health importance beliefs. Overall, we suggest that the versatility of the soil health concept is an asset that aligns across SHPs, and efforts to resolve ambiguity within measurements of 'good' soil health should complement a holistic approach to soil health, which would likely further resonate with practitioners.

Data statement

All data and code generated in this study have been deposited in Ag Data Commons (10.15482/USDA.ADC/28723664) (Hammond Wagner et al., 2025). All code was written using R statistical software (version 4.4.1).

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CRediT authorship contribution statement

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Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.soisec.2025.100186.

Data availability

Data and code are available via DOI link on Ag Data Commons.

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