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Abbreviations: D_b, bulk density; K_S, saturated hydraulic conductivity; NAPESHM, North American Project to Evaluate Soil Health Measurements; SOC, soil organic carbon; WSA, water stable aggregate percentage; θ_{FC_INTACT}, volumetric water content at field capacity measured on intact cores; θ_{FC_REPACK}, volumetric water content at field capacity measured on repacked cores.

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Abstract

Farmers, scientists, and other soil health stakeholders require interpretable indicators of soil hydraulic function. Determining which indicators to use has been difficult because of measurement disconformity, spatial and temporal variability, recently established treatments, and the effect of site characteristics on management practice differences. The North American Project to Evaluate Soil Health Measurements includes 124 sites uniformly sampled across a range of soil health management practices in North America in 2019. We compare and recommend indicators of hydraulic function that best characterize soil health. We assessed the relationship of each indicator to a suite of soil inherent properties and climate variables, the response of each indicator to soil health management practices, the effect that soil inherent properties (clay content, sand content, and pH) and climatic variables (10-yr mean annual precipitation and temperature) had on response to management practices, and the relationship among the responses of the indicators to soil health management practices. Field capacity measured on intact cores (θ_{FC_INTACT}) was the best measure of soil hydraulic function, because it responded to management, represents a direct measure of soil hydraulic function, is proximal to stakeholder values, and its response to management was not significantly influenced by inherent and climatic variables. Other suitable indicators are bulk density, soil organic carbon (SOC), and aggregate stability, which are not direct measures of soil hydraulic function but do respond to management and may be practical in situations in which measuring θ_{FC_INTACT} is not. This study informs selection of soil health indicators to measure soil hydraulic function.

1 | INTRODUCTION

A critical function of healthy soil is the ability to capture, store, and release water while preventing water erosion. Consequently, improving this soil function is a goal of soil health management systems. Improving soil hydraulic function is a motivating factor for farmers to adopt soil health management practices (practices that follow USDA-NRCS soil health management principles) (Bossanage et al., 2016; Romig et al., 1995) and is of growing importance due to increased temperature and precipitation variability caused by climate change (Liang et al., 2017; Schipanski et al., 2016). To quantify the effect of soil health management practices on ecosystem services that flow from soil hydraulic functions, indicators of various aspects of soil water cycling, storage, and erosion risk are needed.

There is a deficiency of data for a continental analysis of the effects of soil health management practices on indicators of soil hydraulic function. This deficiency occurs for many reasons: methodological differences in the measurements, spatial and temporal variability, treatment duration, and the inherent differences in the response of soil types to management practices. A review of the effects of tillage on soil hydraulic function found that reductions in tillage tended to improve hydraulic function, but spatial and temporal variability often overshadow management effects (Strudley et al., 2008). The review also noted that sampling timing, both within a season and since a management change, complicates assessment. No-till fields have more seasonally stable hydraulic properties compared with tilled fields, though they take years to reach equilibrium (Strudley et al., 2008). Conversely, tillage events amplify seasonal variation in hydraulic properties (Strudley et al., 2008). Temporal variability has been shown to be greater than spatial variability of hydraulic soil properties (van Es et al., 1999). A meta-analysis of 89 studies comparing conventional and alternative practices found that no-till significantly increased infiltration only in wetter climates (Basche & DeLonge, 2019), demonstrating interactions between management and climate. Thus, consistent sampling time and evaluation on established (>10 yr) treatments are critical for comparing management effects.

Contrasting conclusions about the effects of management on soil hydraulic function also arise when different measurement methods are used. For example, indicators of infiltration are dependent on the method used (Castellini et al., 2020) and on antecedent moisture content (Stewart et al., 2018). As well, the effects of soil organic carbon (SOC) (an indicator of management) on plant available water can be small when field capacity is measured on clods or disturbed samples (Minasny & McBratney, 2018), but when intact cores are used the increase in plant available water in response to greater SOC can be substantial (Bagnall et al., 2022; Bean & Soil Health Institute, 2020) and such changes are economically relevant to farmers (Kane et al., 2021). Lastly, inherent soil properties influence how changes in management affect soil hydraulic function. For example, soil texture greatly influences the response of bulk density and total porosity to management (Hakansson & Lipiec, 2000). Texture also affects the response of soil structure, saturated hydraulic conductivity, and aggregate stability to tillage (Bagnall & Morgan, 2021). With so many variables and their interactions at play, a uniform sampling design with geographic distribution is needed to augment existing knowledge (Basche & DeLonge, 2019; Strudley et al., 2008).

In addition to being sensitive to changes in soil management and relevant across climates and soil types, hydraulic soil health indicators are more useful for communication if they are also proximal, or benefit relevant, to stakeholder values (Boyd et al., 2014; Doran & Ziess, 2000; Ingram et al., 2016; Reimer et al., 2014). Indicators are proximal to stakeholder's values when they are interpretable and meaningful to that stakeholder (Boyd et al., 2014). Such proximal indicators have greater value or weight in decision-making relative to less proximal indicators. Stakeholders include farmers, those that invest in commercial agriculture, those that consume agricultural products, and those who are affected by the flow of ecosystem services (or lack thereof) from agricultural land. An example of a proximal indicator is plant available water because farmers understand that increased capacity of soil to store water relates to the health of their crops (Bagnall et al., 2020). Farmers can quickly and easily decide whether a quantity of plant available water is large enough to provide an incentive for them to adopt a soil health management practice. In contrast, an indicator such as aggregate stability is less proximal to a farmer's value because the benefits of a percentage change in aggregate stability are less clear; some studies have related aggregate stability measurements to erosion and infiltration (Barthès & Roose, 2002), but correlations are not consistent (Amèzketa, 1999). Although proximal indicators are easy to interpret, they may be difficult, time-consuming, and costly to measure or they may not be sensitive to management changes. If a strong relationship exists between two indicators of soil health, it may be preferable to measure the less proximal indicator if it is easier, quicker, or more affordable to measure.

The North American Project to Evaluate Soil Health Measurements (NAPESHM) (Norris et al., 2020) provides an opportunity to evaluate soil health indicators because it includes a consistent suite of direct and indirect measures of soil hydraulic function as well as those that are expected to have functional relationships with soil water dynamics. Soil health indicators in NAPESHM were uniformly sampled at 124 sites across North American in 2019 and were measured across treatments representing a variety of soil health management practices. Direct indicators of hydraulic function measured for this project were water retention at field capacity, water retention at permanent wilting point, and saturated hydraulic conductivity (Figure 1) because these indicators reflect movement or storage of water. Less direct indicators of hydraulic function were bulk density, SOC, and aggregate stability because they represent physical soil properties that determine water movement or, in the case of SOC, soil composition that influence those physical properties.

The goal of this study was to compare and recommend soil health indicators of soil hydraulic function. Because soil hydraulic function is strongly influenced by management and inherent site characteristics, such as inherent soil properties (e.g., clay content) and climate (e.g., mean annual temperature), we also aimed to consider the relationship between the soil health indicators and site characteristics. Specifically, we assessed (a) the relationship of each indicator to a suite of soil inherent properties and climate variables, (b) the response of each indicator to soil health management practices, (c) the effect that soil inherent properties and climatic variables had on the response of indicators to management practices, and (d) the relationship between the responses of the indicators to soil health management practices. Equipped with an improved understanding of how these uniformly collected measurements respond to management changes and how the magnitude of changes interact with site characteristics, we discuss the value of each measurement with respect to proximity to benefit relevant values of stakeholders and practicality of measurement. The results contribute to the goal of the NAPESHM project of a minimum suite of soil health indicators to scale soil health assessment continentally.

Core Ideas

- Across sites, management changed aggregate stability, C, and bulk density.
- Management also changed field capacity for intact cores, but not repacked cores.
- Increased residue, organic nutrient sources, less tillage, each increased field capacity by 4%.
- Residue retention, organic nutrients and less tillage reduced bulk density by 2–3%.
- Field capacity for intact cores was the most responsive and direct indicator.

2 | MATERIALS AND METHODS

The NAPESHM project sampled a range of soils and management practices using a uniform sampling strategy at research sites (Norris et al., 2020). This was accomplished through a collaborative effort between a team of scientists at the Soil Health Institute (SHI) and more than 95 partnering scientists that managed sites across Canada, Mexico, and the United States. All soil health indicators except saturated hydraulic conductivity (K_S) were sampled at 124 sites. For K_S, 119 sites were measured, and the sites not measured were located in Wisconsin, Ohio, Iowa, and Louisiana. Soil orders in the dataset included the Soil Taxonomy orders of Ultisol, Alfisol, Mollisol, Vertisol, Aridisol, Inceptisol, and Entisol. Each site had between one and four treatment replicates, and more than 2,000 experimental units (either plots or fields that represent one replication of a treatment) from 688 treatments

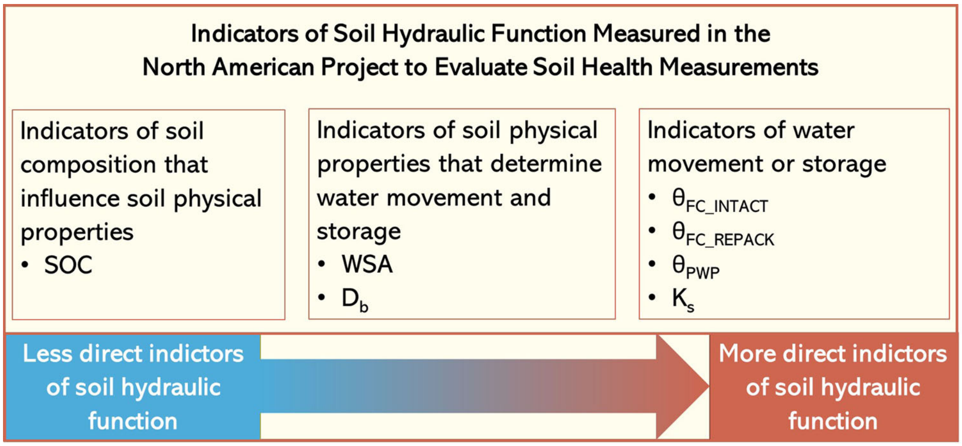

FIGURE 1 Conceptual graphic of the soil health indicators related to soil hydraulic function measured in the North American Project to Evaluate Soil Health Measurements. Indicators include water stable aggregate percentage (WSA), bulk density (D_b), permanent wilting point (θ_{PWP}), field capacity measured on repacked (θ_{FC_REPACK}) and intact (θ_{FC_INTACT}) cores, saturated hydraulic conductivity (K_S), and soil organic carbon (SOC)

were sampled across all sites. Of the 124 sites, 13 had one replicate per treatment. Treatments consisted primarily of differences in tillage, cover crops, organic nutrient sources, cash crop count, residue retention, and rotation diversity. All but six sites were sampled between February and July of 2019, and all but 19 sites were sampled at least 1 mo prior to any spring soil management such as tillage, planting, or fertilizer application. Soil, weather, historical site management, and yield data were collected for each treatment.

2.1 | Sample collection

Soils were sampled at four to six locations within each experimental unit (each replicate of each treatment). For each location, a 15- × 15- × 15-cm soil core was removed. From the resulting hole, a 15- × 4-cm soil slice was taken from three of the four sides (the side used to pry the soil core out was avoided due to possible soil compaction). These three soil slices were then composited with the other soil slices within the experimental unit. As a result, 12–18 soil sample slices were to a depth of 15 cm combined for each experimental unit composite (bulk) sample.

Four soil bulk density (D_b) samples were collected, 7.65 cm in diameter and from 0 to 7.65-cm deep, in each experimental unit (core method) (Blake & Hartge, 1986). The D_b cores were collected using hand pressure when possible and a slide hammer when necessary. Where previous crop rows could be detected, two D_b samples were collected in the row and two between rows. Two cores, one each representing in-row and between-row when possible, were collected in individual protective plastic sleeves, capped on either end, and used for both the calculation of D_b and field capacity measured using an intact core (θ_{FC_INTACT}). The remaining two D_b cores were composited into one bag, sieved to remove coarse fragments >2 mm, and used for Db calculation only.

One K_S measurement was collected in situ for each experimental unit using SATURO Infiltrometers (Meter Group, Inc.). This automated tool uses the two-ponding head analysis method (Reynolds & Elrick, 1990). The SATURO reference guide was consulted to configure the settings to accommodate field-specific soil conditions. The default infiltrometer ring was inserted to 5-cm deep. The 10-cm deep insertion depth was used in coarse-textured or low bulk density soils when the 5-cm ring did not sit tightly in the soil. The 10-cm deep ring was also used in soils when the flow rate was high enough to prevent a steady-state water level with the 5-cm deep ring.

2.2 | Laboratory analysis

Soil particle size analysis, pH, and SOC were measured at The Ohio State Soil Water and Environmental Lab. Aggregate stability, bulk density, and all measures of water retention were measured at the Cornell Soil Health Laboratory (Ithaca, NY). The composited soil sample consisting of 12–18 soil slices was used for particle size analysis total organic C, pH, and aggregate stability . Soil texture was measured using the pipette method and sands were wet sieved (Gee & Bauder, 1986). For particle size analysis, a dispersing solution was made by dissolving 35.7 g sodium hexametaphosphate and 7.94 g sodium carbonate per liter of H_2O. Total organic C was measured using the dry combustion method (Nelson & Sommers, 1996) using an NC 2100 soil analyzer made by CE instruments . Soils that effervesced with 1 M HCl were analyzed using the Chiddicks method for total inorganic C (Dreimanis, 1962). Soil organic C was calculated as the difference between total organic C and inorganic C. Soil pH was measured in a one-to-two water dilution (Thomas, 1996). Aggregate stability was measured as fraction (expressed in percentage) of water stable aggregate percentage (WSA) using the Cornell wet aggregate stability test (Moebius-Clune et al., 2016).

The composited D_b samples were processed only for D_b. For any experimental unit with <2% coarse fragments (>2 mm) by weight (determined during preparation for particle size analysis), D_b was calculated as the mean of intact and composited D_b samples. For 199 experimental units with coarse fragments >2% by weight, D_b was calculated as the mean of two composited cores, following removal of, and adjustments for, coarse fragments.

Two methods were used to calculate water retention at field capacity. One method used ground and repacked composited soil and measured field capacity at 10 kPa using porous ceramic pressure plates in pressure chambers, θ_{FC_REPACK} (Reynolds & Topp, 2008). The second method used the intact soil cores to measure field capacity at −33 kPa on tension tables, θ_{FC_INTACT} (Hao, et al., 2008; Topp, et al., 1993). Permanent wilting point (θ_{PWP}, defined as −1,500 kPa) was measured on repacked cores of composited soil on pressure plates (Reynolds & Topp, 2008).

2.3 | Statistical analyses

Data were analyzed using RStudio Version 1.2.5001, and statistical significance was set at the 95% level of confidence ($p < .05$). The coefficient of variation was calculated by treatment within sites when there were at least three replicates per treatment and was plotted to compare the variability among soil health indicators. Multiple linear regressions using the stats package in R (Chambers, 1992) were used to determine the relationships between each of the soil health indicators (WSA, D_b, θ_{PWP}, θ_{FC_REPACK}, θ_{FC_INTACT} , K_S, and SOC) and soil inherent and climatic variables. Soil inherent variables were clay content, sand content, and pH. Climatic variables were 10-yr mean annual total precipitation and average temperature. Calculation of the 10-yr mean temperature and precipitation was done using the DayMet (Thornton et al., 1997) via the daymet package in R. We did not include irrigation water applied to better represent inherent site environments. Histograms were used to determine whether variables required transformation prior to being included in linear models. We used site means of all variables for analyzing the relationship between soil health indicators and soil inherent properties in multiple linear regressions.

The effect of management practices on soil health indicators was assessed using log response ratios of paired treatments within each site. We used the rma.mv function in the metafor package (Viechbaur, 2010) to fit a meta-analytic model to predict log response ratios controlling for site as a random variable and weighting by the number of replications of treatment pairs at each site. The log response ratios (hereafter, response ratios) were the natural log of the ratio between individual soil health measurements for two treatments that were appropriate comparisons, that is, two treatments that had only one management difference between them. Soil health indicators were determined to have a significant response to management if the 95% confidence interval, which was calculated by the meta-analytic model, did not contain zero. Response ratios were transformed to percentage change for ease of interpretation.

The management practices used to select appropriate pairs of comparisons in the response ratio analysis included tillage intensity, cover crops (grasses and mix), organic nutrient source type (synthetic or organic), crop residue retention, and cropping system diversity. Sites with any mechanical soil disturbance treatments were grouped into disturbance categories using the following method. The type and frequency of equipment used were cataloged for each treatment, and a standard tillage intensity rating (STIR) value for each operation that disturbed the soil was assigned (USDA-ARS, 2008). Paired treatments were included if the management was the same except for the tillage practices and if the maximum STIR value or the sum of the STIR values for the rotation differed. Treatment pairs were excluded if the difference in STIR was only due to differences in planting equipment.

Cover crops were treated as a categorical variable for presence or absence of cover crops. A cover crop was any crop that was planted, present for <1 yr, and was terminated by herbicides, fall frost, or tillage, but not harvested. We did not include any treatment pairs that compared types of cover crops. Organic nutrient source management was assigned to a treatment where biosolids, compost, or manure at least partially replaced synthetic fertilizer. Management for crop count compared monocultures to rotations with at least two different crops of any kind (not including cover crops). Rotation diversity compared rotations of only grain crops to rotations with nongrain crops. The nongrain crops included legumes (Fabaceae), canola (*Brassica napus* L.), safflower (*Carthamus tinctorius* L.), and cotton (*Gossypium hirsutum* L.), with legumes being the most common. Residue removal compared treatments in which crop rotation was identical, but the amount of residue removed was not. Selecting appropriate pairs resulted in subsets of the sites and treatments used to represent each management practice (Table 1).

Because the goal of our study was to compare and recommend soil health indicators of soil hydraulic function, we conducted all analyses on the three measures of water retention (θ_{PWP} θ_{FC_INTACT} , and θ_{FC_REPACK}) separately. This allowed us to clearly differentiate the signals of the measures and to demonstrate how they are different from one another. Because we recognize the importance of quantifying the effect of management on plant available water, we calculated plant

TABLE 1 Number of sites and soil health treatments for each management practice used in response ratio analysis

Management practice	Treatment: Control	Treatment pairs	Sites
Rotation diversity	More than one crop type: Only grains	63	24
Crop count	More than one cash crop: One cash crop	199	33
Residue retention	Residue retained: Residue removed	54	14
Organic nutrient sources	Organic nutrient sources: Synthetic nutrient sources	32	13
Cover crops	Cover crops: No cover crops	21	10
Decreased tillage	Lower tillage: Higher tillage	160	51

available water for select values in the discussion to illustrate the benefits of soil health management practices. As well, we conducted the response ratio analysis with plant available water and verified that our interpretations of the separate response ratio analysis for θ_{PWP} and field capacity did not alter the significance or interpretation of the results. Having confirmed that our analysis did not overestimate the magnitude of the benefits of soil health management in terms of plant available water, we reported results for θ_{PWP} , θ_{FC_INTACT} , and θ_{FC_REPACK} independently.

To explore how inherent soil and climatic variables affected the response of soil health indicators to management practices, we fit multiple linear regressions to response ratios for tillage averaged by site (site mean response ratios) for each indicator. The predictors were clay and sand content, pH, precipitation, and temperature, plus their two-way interactions. We used interaction plots to explore conditional effects (accounting for all predictor variables in the model) of significant two-way interactions using the interact_plot function (Bauer & Curran, 2005; Cohen et al., 2003; Hainmueller et al., 2016) from the interactions package in Rstudio. We used default settings for interact_plot (modx.values = "mean-plus-minus"). This default function displayed the effect of each significant interaction term on the response ratio of the soil health indicator to management by using one predictor from the interaction as a continuous variable on the *x* axis and the second predictor variable of the interaction term as three regression lines. The lines illustrate the mean of that variable, the mean plus one standard deviation, and the mean minus one standard deviation.

To better understand how the responses of soil health indicators to management relate to one another, we created correlation matrices between the responses of indicators to management. We only showed and discussed correlation matrices if indicators of hydraulic function had a statistically significant response to management for the response ratio analysis described above.

Table 2 reports descriptive statistics for site means of soil health indicators. The indicators θ_{PWP}, θ_{FC_REPACK}, θ_{FC_INTACT} , and D_b were normally distributed and had means and medians that were <7% different from one another. Conversely, K_S, SOC, and water stable aggregate (WSA) were log-normally distributed and had means that were 27, 13, and 19% greater than their respective medians. In this analysis, K_S, SOC, and WSA were log-transformed prior to being included in multiple linear regressions.

3 | RESULTS AND DISCUSSION

3.1 | Relationship of indicators to inherent properties and climate variables

The multiple linear regressions for soil health indicators explained by inherent properties and climate variables had adjusted R^2 values ranging from .18 for the log of WSA to .83 for θ_{PWP} (Table 3). The model for K_S was not significant ($p > .05$) so K_S was not included in Table 3. The three measures of water retention (θ_{PWP}, θ_{FC_REPACK}, θ_{FC_INTACT}) were the indicators most strongly related to inherent properties and climate variables and had adjusted R^2 values of .83, .79, and .77, respectively. Soil texture is well known to be the primary driver of water retention at field capacity and especially at permanent wilting point. Many pedotransfer functions use clay and sand content to predict water retention (Børgesen et al., 2008; Lal, 1979; Rawls et al., 1982; Saxton & Rawls, 2006). The adjusted R^2 for the log of SOC and for D_b were smaller, but still substantial (.48 and .37, respectively). The fact that inherent soil properties and climatic variables influence SOC and D_b is consistent with pedogenesis concepts (Jenny, 1946) and supported in the literature (Callesen et al., 2003; Rawls, 1983; Strudley et al., 2008).

The soil health indicator least related to inherent properties and climate variables was WSA with an adjusted R^2 of .18. The dependence of aggregate stability on inherent soil properties and climatic variables has mixed results in the literature (Bradford et al., 1987;Fajardo et al., 2016; Lado et al., 2004; Skidmore & Layton, 1992). Aggregate stability is a complex property influenced by internal factors (clay mineralogy, content of $CaCO_3$, gypsum, Fe and Al oxides, and organic C) and external factors (climate, ageing, roots, soil microbes, soil fauna, and agricultural management) as well as the fact that several different methods of aggregate stability are commonly used (Amézketa, 1999).

TABLE 2 Descriptive statistics for means by site including, water stable aggregate percentage (WSA), bulk density (D_b), permanent wilting point (θ_{PWP}), field capacity measured on repacked (θ_{FC_REPACK}), and intact (θ_{FC_INTACT}) cores, saturated hydraulic conductivity (K_S), and soil organic carbon (SOC)

Statistic	WSA	D_b	θ_{PWP}	θ_{FC_REPACK}	θ_{FC_INTACT}	K_S	SOC
	%	Mg m^{-3}	m^3 m^{-3}	m^3 m^{-3}	m^3 m^{-3}	cm hr^{-1}	g kg^{-1}
Min.	7	0.64	0.02	0.12	0.10	1.1	0.33
Max.	71	1.61	0.25	0.66	0.43	99.5	8.87
Mean	27	1.21	0.12	0.42	0.30	19.6	1.72
Median	22	1.23	0.12	0.43	0.32	14.2	1.50
SD	15	0.17	0.05	0.11	0.07	16.8	1.01

TABLE 3 Adjusted R^2 of multiple linear regressions for site mean water stable aggregate percentage (WSA), bulk density (D_b), permanent wilting point (θ_{PWP}), field capacity measured on repacked (θ_{FC_REPACK}) and intact (θ_{FC_INTACT}) cores, and soil organic carbon (SOC) predicted by inherent soil properties and climate variables

Indicator	Coefficients					R^2 adjusted
	Sand	Clay	Temperature	Precipitation	pH	Full model
	——%——		°C	mm		
θ_{PWP}	–	+			+	.83
θ_{FC_REPACK}	–			+	+	.79
θ_{FC_INTACT}	–	+	–	+		.77
Log(SOC)		+	–	+		.48
D_b		–		+		.37
Log(WSA)	+	+	–	+	–	.18

Note. The SOC and WSA variables were log transformed. Soil inherent properties were site means of sand content, clay content, and pH. Climatic variables were site means of annual temperature and annual precipitation. A + or – indicates the sign of the regression coefficient and no symbol indicates that the *p* value for that regression coefficient was not significant at .05.

The fact that the regression for K_S predicted by inherent and climatic variables was not significant was unexpected given that studies have shown that inherent soil properties, especially clay and sand content, can be used to predict soil hydraulic properties (Leij & van Genuchten, 1999; Lin et al., 1999a;Rawls et al., 1991; Schaap et al., 2001; van Genuchten & Leij, 1992;Zhang & Schaap, 2017). Indeed, K_S parameters for hydrology models are frequently parameterized using only soil texture information (Rawls et al., 1982). Some studies have reported that soil texture does not significantly influence infiltration across sites (DeLonge & Basche, 2017). The spatial distribution of K_S is log-normal and related to preferential flow paths (Baldock & Nelson, 2000; Lin et al., 1998; Mapa, 1995; Reynolds & Zebchuk, 1996) resulting in high spatial variability across a landscape (Gupta et al., 2006; Lin et al., 1998; Lin et al., 1999a; Lin et al., 1999b; Sobieraj et al., 2002). Though all analyses included multiple replications of each treatment, because K_S in the NAPESHM project was measured only once in each experimental unit (Norris et al., 2020), we likely did not collect enough measurements to capture the true mean of K_S in each experimental unit (Bouma, 1982). The coefficient of variation for K_S was more than four times larger than the coefficient of variation for any other soil health indicator (Figure 2). This high CV may be due to the fact that only one replication of K_S was taken at each experimental unit, the natural variability of K_S, or some combination of these two factors. In the remainder of our study, we interpret results related to K_S in context of this large variation and the fact that differences in K_S due to management are commonly overshadowed by spatial and temporal variability (Strudley et al., 2008).

Sand content was a significant predictor in all regressions except those for D_b and the log of SOC (Table 3) and had a negative effect on water retention indicators and a positive effect on WSA. The positive effect of sand on WSA occurred because the procedure corrects for coarser sand particles (but not fine or very fine) by rinsing the stable aggregate fraction remaining after rainfall simulations through a 0.25-mm sieve (Moebius-Clune et al., 2016). Therefore, soils with higher fractions of fine and very fine sands may have inflated measures of WSA. However, this measurement was designed to be used in the Comprehensive Assessment of Soil Health (CASH), which uses a scoring function that requires values of WSA in coarse soils than in fine soils to achieve a "good" rating (Fine et al., 2017). Though the CASH test accounts for the positive effect of sand on WSA using scoring functions,

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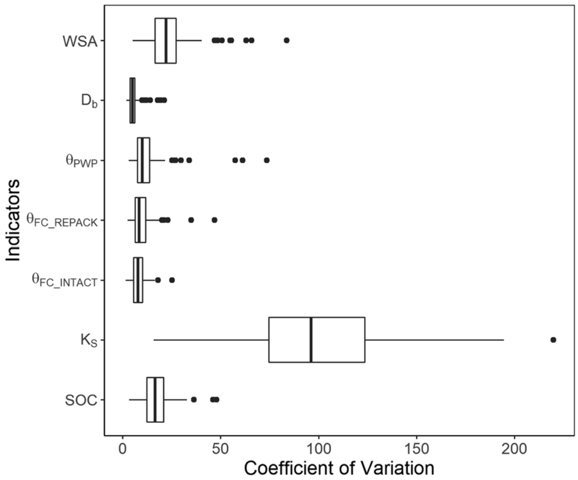

FIGURE 2 Boxplots of coefficients of variation for soil health indicators by treatment within sites: Water stable aggregate percentage (WSA), bulk density (D_b), permanent wilting point (θ_{PWP}), field capacity measured on repacked (θ_{FC_REPACK}) and intact (θ_{FC_INTACT}) cores, saturated hydraulic conductivity (K_S), and soil organic carbon (SOC)

users of WSA not applying the scoring functions should recognize this increase in WSA with increased sand does not represent greater soil health in sandy soils. The finding that increased sand content reduces water retention is consistent with previous work and our understanding of the physics of water retention in soil (Lal, 1979; Rawls et al., 1982; Saxton & Rawls, 2006). Clay content was a significant predictor for all soil health indicators except θ_{FC_REPACK} and the influence is opposite to that of sand except for WSA. The lack of significance for clay as a predictor of θ_{FC_REPACK} is explained by the strong negative correlation between sand and clay content; both the overall model and the clay coefficient were significant when sand was removed from the regression.

Temperature had a negative effect on θ_{FC_INTACT}, log of SOC, and log of WSA, indicating that higher temperatures lead to lower θ_{FC_INTACT}, log of SOC, and log of WSA. Colder temperatures are associated with SOC accumulation (Jackson et al., 2017) and the SOC has been associated with higher water retention at field capacity and greater aggregate stability (Baldock & Nelson, 2000; Jiang et al., 2007; Mapa, 1995). It is notable that temperature had a significant negative effect on θ_{FC_INTACT} and not on θ_{FC_REPACK} and we propose this is due to a stronger relationship between SOC and θ_{FC_INTACT} compared with θ_{FC_REPACK}.

Precipitation had a significant, positive effect for all indicators except θ_{PWP}; it was the predictor most consistently correlated with all of the indicators. Similar to temperature, the effect of precipitation on soil health indicators is likely due to greater biomass production and a higher occurrence of anaerobic microsites, hence greater SOC accumulation at wetter sites (Jackson et al., 2017; Keiluweit et al., 2017).

Soil pH was a positive significant predictor of θ_{PWP} and θ_{FC_REPACK}, and a negative predictor of WSA. Multiple studies have found that clay dispersion increases with increasing soil pH. A review reported that multiple studies found that greater pH values were associated with greater clay dispersion (Strudley et al., 2008), and this likely drives lower WSA at high pH. The relationship between pH and water retention may be governed by clay mineralogy: higher pH soils have greater amounts of 2:1 clays (Keller & Matlack, 1990), which drives greater water retention (Macek et al., 2013). The effect of pH on water retention was significant for disturbed samples (PWP and θ_{FC_REPACK}), but not for intact cores (θ_{FC_INTACT}) likely because the variance in intact cores was largely driven by differences in soil structure.

3.2 | Response of indicators to changes in management practices

The response ratios for all soil health indicators to reduced tillage, addition of organic nutrient sources, addition of cover crops, increased number of cash crops, increased rotation diversity, and residue retention were transformed to percentage change for ease of interpretation (Figure 3). The response of an indicator to a change in management practice is significant when the 95% confidence interval does not include zero. Increased residue retention (Figure 3c), use of cover crops (Figure 3e), and reduced tillage (Figure 3f) each increased WSA by about 20%; thus, although WSA is not a proximal indicator of soil hydraulic function, it is clearly sensitive to management. The response of aggregate stability to changes in management is well documented (Amézketa, 1999; Bagnall & Morgan, 2021; Fajardo et al., 2016) and has led to it being a common indicator of soil health (Stewart et al., 2018). In the following sections, we explore whether changes in WSA due to management are correlated with responses to management of more proximal indicators of soil hydraulic function.

Bulk density decreased by 2–3% with greater residue retention (Figure 3c), addition of organic nutrient sources (Figure 3d), and reduced tillage (Figure 3f), independently. However, rotation diversity increased D_b by about 3%. Measurements of D_b have been recommended as a chief indicator of changes in soil hydraulic function due to tillage (Soane et al., 2012) and were collected in about half of the 196 soil health studies that Stewart et al. (2018) reviewed to assess which measures of soil health were most common. It has also been shown that D_b is inversely related to soil infiltration rate (Azooz & Arshad, 2001) and is spatially correlated to crop yield within fields (Castellini et al., 2019). Pilon et al. (2017) found that increases in bulk density due to grazing from cattle resulted in higher runoff volumes from pastures and increased soil erosion. Likewise, Anderson et al. (2020) found that increased runoff volumes led to significant increases in

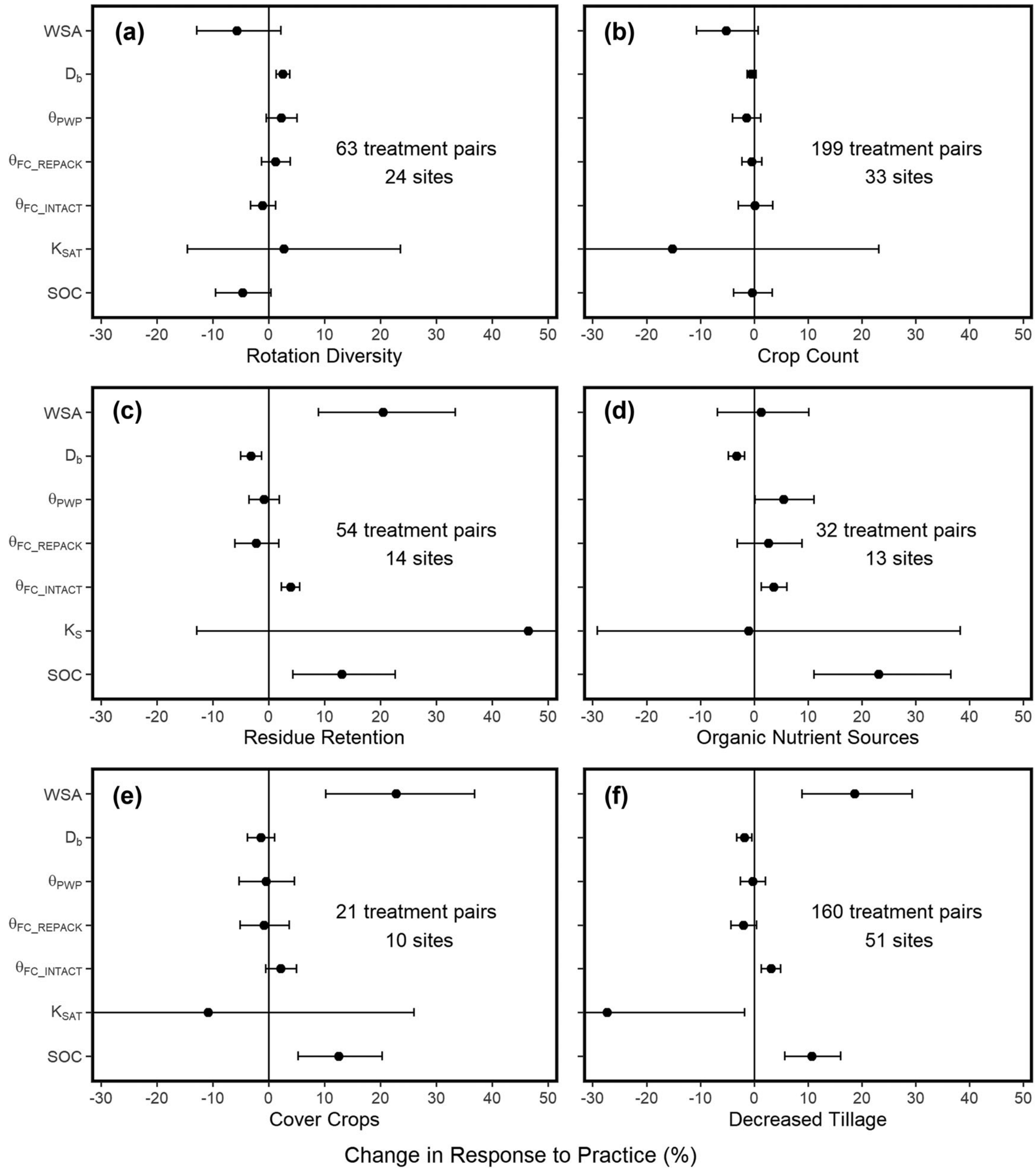

FIGURE 3 Response ratios for soil health indicators by management practice. Black dots are means and bars represent 95% confidence limits. Water stable aggregate percentage (WSA), bulk density (D_b), permanent wilting point (θ_{PWP}), field capacity measured on repacked (θ_{FC_REPACK}) and intact (θ_{FC_INTACT}) cores, saturated hydraulic conductivity (K_S), and soil organic carbon (SOC)

P runoff. Some studies have found that D_b is not changed by tillage (Khaledian et al., 2012; Strudley et al., 2008), making it important to investigate interactions between soil management and other drivers of variance in D_b.

None of the management practices significantly affected θ_{PWP} or θ_{FC_REPACK}, indicating that variance in these two indicators is primarily driven by inherent soil properties (Table 3), rather than changes in management. This finding supports previous work that shows little effect of management (Nunes et al., 2018; van Es & Karlen, 2019) and SOC, an indicator of management, on plant available water holding capacity (Minasny & McBratney, 2018). However, when intact cores were used to measure field capacity, significant effects of management were detected across the locations in this study. Specifically, residue retention (Figure 2c), addition of organic nutrient sources (Figure 3d), and reduced tillage (Figure 3f) each increase θ_{FC_INTACT} by between 3 and 4% (value relative to the base, not percentage water content). If a given management increased field capacity by 4% and did not alter θ_{PWP}, the additional plant available water holding capacity (field capacity minus θ_{PWP}) to a depth of 15 cm would be 0.18 cm. If this capacity were filled through irrigation or rainfall five times throughout a growing season, this would result in an additional 0.90 cm (0.36 in) of water provided to the crop. This amount of additional plant available water represents the mean response to residue retention, addition of organic nutrient sources, and reduced tillage in NAPESHM data. The maximum response of θ_{FC_INTACT} to management was a 10% change due to addition of organic nutrient sources , and that value would translate to an additional 2.3 cm (1.0 in) of plant available water if it were refilled five times throughout a growing season. This supports findings that plant available water can be increased by soil management (Ankenbaur & Loheide, 2017; Bouyoucos, 1939; Hudson, 1994; Salter & Howarth, 1961) and supports sampling field capacity using intact soil cores to capture the effects of soil health management practices on soil structure (Dane & Hopmans, 2018). The designs of the experiments sampled in NAPESHM constrain us to test individual effects of soil health practices in this meta-analysis, but we speculate that synergies between multiple practices could have even greater effects on plant available water.

The only significant response of K_S to management was a 27% decrease due to reduced tillage. Studies have recorded mixed results regarding the effects of management on K_S (Strudley et al., 2008), shown that there is greater variance in K_S in tilled soils (Oztekin & Ersahin, 2006), and substantial spatial and seasonal variance of K_S (Strudley, 2008; Mapa, 1995; Reynolds &, Zebchuk, 1996; Schwen et al., 2011). Because of the high coefficient of variation in our K_S data (Figure 2), the high variability of K_S, and the fact that K_S data in this study showed unexpectedly weak relationships with soil inherent properties (Table 1), interpretation of the effects of management on K_S using these data are not reliable.

Reduced tillage, use of cover crops, and increased residue retention each resulted in similar increases in SOC (11–13%) and the addition of organic nutrient sources had a 23% increase in SOC. Although not a direct indicator of soil hydraulic function, SOC has been shown to reduce surface sealing and improve soil structure. Both of these effects tend to increase infiltration, improve plant available water (Ankenbaur & Loheide, 2017; Bouyoucos, 1939; Hudson, 1994; Salter & Howarth, 1961), increase aggregate stability (Amézketa, 1999), and reduce bulk density (Strudley et al., 2008). As well, increased SOC stock in soil is of growing interest as a marketable good.

The response ratio analysis found that SOC and D_b were sensitive to the most practices, with four practices being significant for each, though D_b had one response in an undesirable direction (increased D_b). This indicates SOC and D_b are useful for detecting the effects of management practices, though they are not direct measurements of hydraulic function of soil. Both WSA and θ_{FC_INTACT} were sensitive to three of the six practices. Of the two, θ_{FC_INTACT} is a proximal measure of the function of water provision to crops, making it a desirable indicator of soil health in the context of hydraulic function. Although K_S is a measurement strongly related to soil hydraulic function, its high spatial variability prevented reliable calculations of the effect of management on K_S in this study. Neither θ_{PWP} nor θ_{FC_REPACK} showed significant responses to the management practices in this study.

Decreasing tillage had significant effects on most soil health indicators: five of the seven soil health indicators. Addition of organic nutrient sources and increased rotation diversity both had significant effects on four of the seven indicators. Addition of cover crops showed significant effects for only two indicators and (WSA and SOC). It is noteworthy that the mean response of D_b and θ_{FC_INTACT} was similar for cover crops and reduced tillage (Figure 3e,f) but the 95% confidence interval was wider for cover crops, making the results not statistically significant. Increased rotation diversity had only one significant indicator (D_b), and increased crop count showed no significant differences. These results likely depend in part on the number of sites and treatments for each management practice (Table 2). Because cover crop management had similar effects size to tillage but a smaller sample size, additional samples might have made indicator responses to cover crops statistically significant. A meta-analysis of infiltration measurements (Basche & DeLonge, 2019) found that cover crops were more effective at increasing infiltration than no-till across all climates, though no-till showed more effect in wetter climates. Similar to our findings, the meta-analysis showed no effects of crop rotation on soil health indicators of hydraulic function, in this case, infiltration.

Evidence suggests that the most effective soil health management systems for increasing soil hydraulic function are those that keep soil covered, reduce disturbance, and keep continuous living roots in the soil (Basche & DeLonge, 2019) and our results indicate that addition of organic nutrient sources is also effective. Although there is interest in determining which management practices are most effective at achieving soil health, it is likely that synergies among practices show that the greatest effects (Haruna& Nkongolo, 2019; Huang et al., 2020; Pratt et al., 2014). The current study, although comprehensive, does not define limits of what soil health systems can achieve nor what value of an indicator represents a healthy soil; rather the large geographic scope, replicated design, and uniform measurement of data allow us to compare soil health indicators that responded to the management practices observed.

3.3 | Interactions between inherent properties and climate variables on response of indicators to management practices

Multiple linear regressions between site mean response ratios for each management and site mean soil inherent and climatic

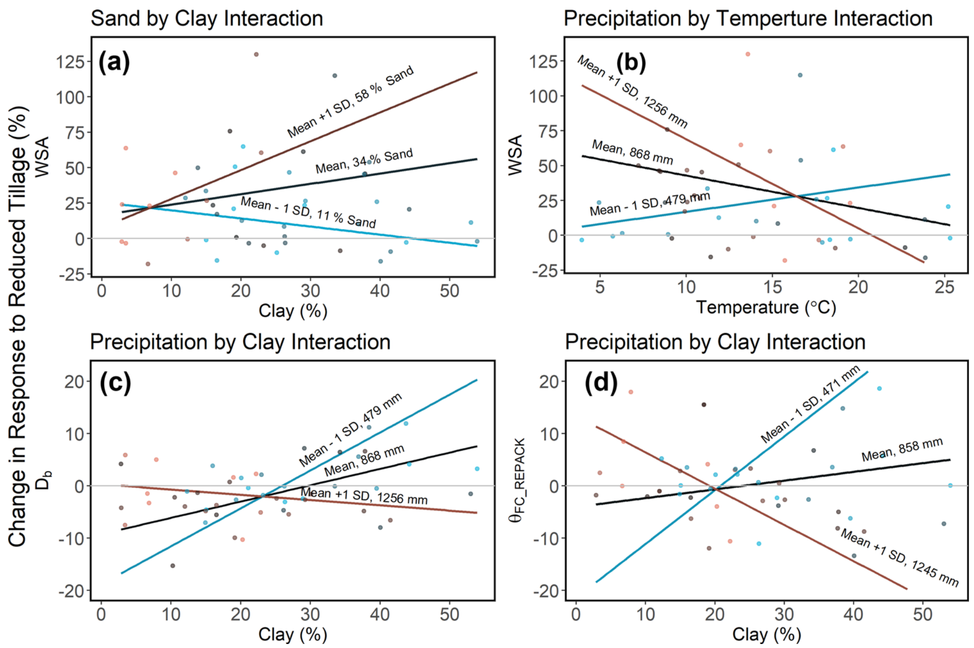

FIGURE 4 Plots for conditional effects (accounting for all predictor variables in the model) of significant two-way interactions from multiple linear regressions. Multiple linear regressions were from predicting the repsonse ratios of water stable aggregate percentage (WSA), bulk density (D_b), and field capacity of repacked soil (θ_{FC_REPACK}) to tillage. Response of soil health indicators to tillage (*y* axis) is plotted against one predictor from the significant interaction term (*x* axis). The second predictor from the significant interaction term is depicted by simple linear regression lines representing predicted values for the mean, and the mean minus (and plus) one standard deviation of the predictor variable. Points represent the conditional response of site mean soil health indicators to tillage and color represents whether they are closer to the mean response (black), one standard deviation above the mean (red) or one standard deviation below the mean (blue)

TABLE 4 Adjusted R^2 of multiple linear regressions of site mean response ratios to tillage with inherent soil properties (site means of sand content, clay content, and pH) and climate variables (site means of annual temperature and precipitation) as predictors

Response variable	Model R^2 adjusted
Response ratio of D_b to reduced tillage	.42
Response ratio of WSA to reduced tillage	.36
Response ratio of θ_{FC_REPACK} to reduced tillage	.28

Note. Response ratios to tillage include water stable aggregate percentage (WSA), bulk density (D_b), and permanent wilting point (PWP). The models included all two-way interactions and had *p* values of <.05.

variables allowed us to assess what proportion of the response of soil health indicators to management was dependent on soil inherent and climatic variables. Only models for tillage were fit because the other management practices had too few sites. The only three significant regressions occurred for response ratios of θ_{FC_REPACK}, D_b, and WSA (Table 4).

We used interaction plots to explore the manner in which inherent and climatic variables influenced the response of θ_{FC_REPACK}, D_b, and WSA to reduced tillage. Figure 4 displays the conditional effect (accounting for all model predictors) of each significant interaction term on the response of the soil health indicator to management by plotting one predictor from the interaction as a continuous variable on the *x* axis and the second predictor variable as three regression lines. The regression lines represent the mean of that variable, one standard deviation below the mean, and one standard deviation above the mean. We included any interaction term that was significant ($p < .05$), and there were no significant main effects that were not also a part of a significant interaction term. The significant interaction terms in the model for the response of WSA to decreased tillage were sand content by clay content and precipitation by temperature. For the models for the response of D_b and θ_{FC_REPACK} to tillage, the only significant interaction term was precipitation by clay content.

In Figure 4a, the regression lines for the mean sand content (34%) and for one standard deviation above the mean sand content (58%) both slope upward with increasing clay content, and the regression line for one standard deviation below the mean slopes downward; this indicates that the response of WSA to reduced tillage was larger (positive slope) with increasing clay content for soils that had sand content at or above the mean 34%. However, at sites with sand content one standard deviation below the mean (11%), the response of WSA to reduced tillage was smaller with increasing clay content (negative slope). The interpretation is that for soils found on the center and left side of the soil texture triangle (>34% sand) greater clay content increases the response of water stable aggregation to decreased tillage. By contrast, for soils with little sand (silt, silt loams, silty clay loams, silty clays, and clays) increasing clay content reduced the response of WSA to reduced tillage. Silty soils can be particularly subject to surface sealing and crusting after a rainfall (Mamedov et al., 2001; Poss & Valentin, 1983). To generalize, soils in this study with greater clay content had larger increases in WSA as a result of reduction in tillage, but soils with little sand were exceptions. Past studies have shown that tillage effects on infiltration and water retention were more pronounced in fine- and medium-texture soils compared with coarse soils (van Es et al., 1999), which is consistent with this study's findings for WSA.

Sites that had greater precipitation (mean plus one standard deviation was 1,256 mm) had less response of WSA to reduced tillage as temperature increased (Figure 4b). By contrast, sites with less precipitation (mean minus one standard deviation was 479 mm) had increased response of WSA to tillage as temperature increased. For sites with the mean precipitation of 868 mm, the response of WSA to temperature was smaller as temperature increased, but to a lesser extent than sites with greater than mean precipitation. This indicates that WSA is less likely to respond to tillage either in dry, cool climates (which likely limit plant growth) or in hot, wet environments (in which SOC is quickly metabolized by microorganisms). The largest response of WSA to reduced tillage was in sites with low temperature and high precipitation, which is consistent with the climatic conditions conducive to SOC accumulation in soils (Jackson et al., 2017).

In Figure 4c, all three regression lines indicate smaller D_b (<0% change) as a result of reduced tillage when soil clay content is less than about 25%. Bulk density decreased due to reductions in tillage at all precipitation levels in lower clay content soils. For sites that had clay content greater than about 25%, only sites in higher rainfall (represented by the mean plus one standard deviation, 1,256 mm) had decreases in D_b. Sites in the mean or lower precipitation areas had increasing response of bulk density to reduced tillage. This means that in general, sites with low clay content had the desired response of D_b to reduced tillage (D_b was decreased due to tillage reductions) but at sites with greater clay content, reducing tillage had the undesirable effect of increasing D_b, except for sites with higher annual precipitation. This means that when reducing tillage on clayier soils (25% clay or more) that receive little precipitation, it may be more critical to use management practices that mitigate compaction such as controlling traffic.

Similar to D_b, the response of θ_{FC_REPACK} to reduced tillage was larger for sites with greater clay content (positive regression slope) if precipitation was at or below the mean (Figure 4d). When precipitation was one standard deviation higher than the mean, this trend reversed such that greater clay content was related to smaller responses of θ_{FC_REPACK} to reduced tillage. Because θ_{FC_REPACK} is reported in volumetric units, observed effects of reduced tillage on θ_{FC_REPACK} are likely driven by the D_b measurements. It is notable that the response of θ_{FC_REPACK} to reductions in tillage had almost a third of its variance explained by soil inherent and climatic variables but the variance in the response of θ_{FC_INTACT} to tillage was not significantly related to soil inherent and climatic variables. Both measures of field capacity were strongly correlated with soil inherent and climatic variables (Table 3) but θ_{FC_INTACT} is more sensitive to management practices (Figure 3) and its response to management is not as dependent on soil inherent properties and climate (Table 4). Hence capturing the effects of management on field capacity is best done using intact cores.

3.4 | Relationship among responses of indicators to management practices

Three of the six management practices (residue retention, organic nutrient sources, and reduced tillage) produced significant responses in more than one of the five hydraulic soil health indicators (Figure 5). Reduced tillage, observed at 51 sites, had the most individual observations in the analyses compared with residue retention, containing 14 sites, and organic nutrient sources, containing 13 sites. Across all managements and indicators, Pearson's correlations between indicator responses to management ranged from −0.5 to 0.5. For all three managements, responses in SOC were positively correlated with responses in θ_{FC_INTACT} and negatively correlated with responses in D_b. For residue retention and reduced tillage, the response of WSA was weakly negatively correlated with the response of D_b (−0.1 to −0.2) and more strongly positively correlated with responses of θ_{FC_INTACT} and SOC (0.3–0.7). The response of K_S to reduced tillage had no correlation with the response of θ_{FC_INTACT} to reduced tillage and weak correlations with responses of D_b, SOC, and WSA to tillage. Correlations between response of SOC and WSA to management were among the strongest observed, being 0.5 for both residue retention and reduced tillage. The Pearson's correlations were mostly weak to moderate, but their directions support the concept that adopting soil health management practices that increase SOC also increase field capacity and aggregate stability while reducing bulk density. It is notable is that the correlations between the response of θ_{FC_INTACT} and D_b are weaker than −0.5; if the effects of management on θ_{FC_INTACT} responses were primarily driven by D_b, we expect there would be stronger correlations. We interpreted this to mean that θ_{FC_INTACT} captures the effects of management on soil structure beyond only the information contained in D_b.

3.5 | Selecting soil hydraulic properties as indicators of soil health

Results relating to the influence of soil health management on K_S were not able to be determined in this study because we did not capture the true mean K_S due to the small number

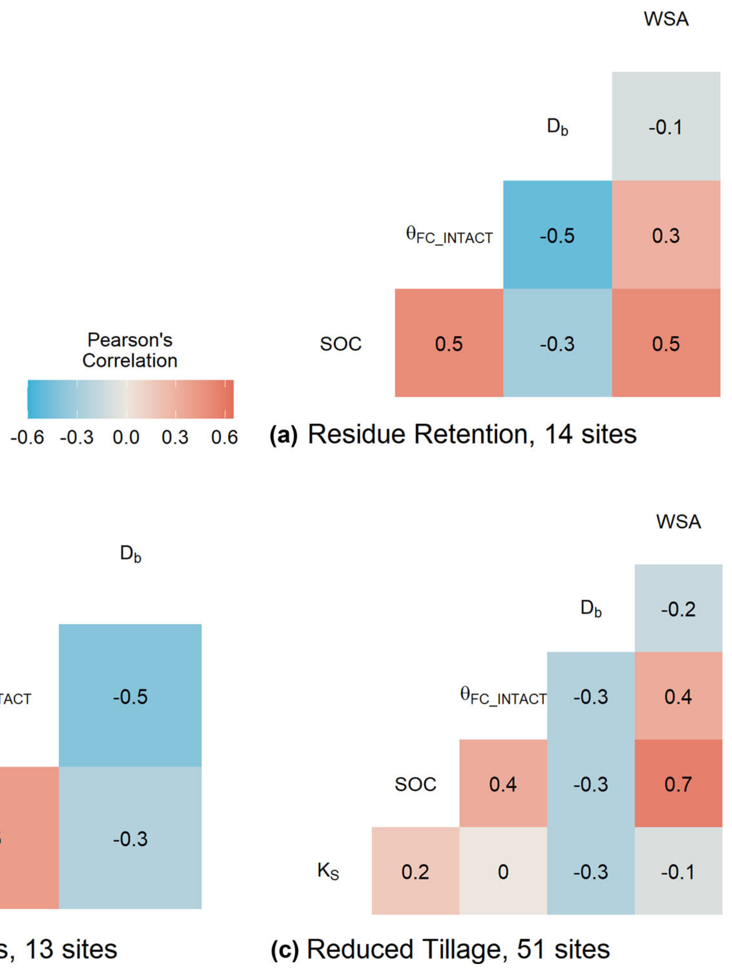

FIGURE 5 Pearson's correlation coefficients between response ratios for soil health indicators for the treatments of residue retention, nutrient type, and reduced tillage. Soil health indicators are water stable aggregate percentage (WSA), bulk density (D_b), field capacity measured on intact (θ_{FC_INTACT}) cores, saturated hydraulic conductivity (K_S), and soil organic C (SOC). Blue colors indicate negative Pearson's correlations, cream colors indciate zero correlation, and red colors indicate positive correlations

of readings taken per experimental unit. Other experimental designs have captured changes in K_S in response to management (Basche & DeLonge, 2019; DeLonge & Basche, 2017). However, the large number of samples needed, and the length of time needed to take a sample, may make it infeasible to scale measurement of K_S for a continental assessment. Measures of water retention taken on disturbed soil samples (θ_{FC_REPACK} and θ_{PWP}) had the strongest relationship with inherent soil properties and climatic variables and did not have significant responses to any of the management practices in this study, similar to findings be Pangagea et al. (2021). So, we do not recommend using θ_{FC_REPACK} and θ_{PWP} as indicators of changes in soil health. They may be valuable measures for other purposes; θ_{PWP}, in particular, is used to calculate available water holding capacity. Although θ_{FC_INTACT} also had a strong relationship with inherent and climatic variables, it showed significant increases (3–4% on average) in response to residue retention, addition of organic nutrient sources and reduced tillage, making θ_{FC_INTACT} a desirable indicator for assessing changes in soil health. Moreover, θ_{FC_INTACT} is a direct measure of the soil hydraulic function of water retention, is proximal to stakeholder values because it is used to calculate plant available water, and integrates changes in soil structure, which are prerequisite for improved soil hydraulic function. We recommend θ_{FC_INTACT} as the most useful indicator for those who wish to directly measure changes in soil hydraulic function. Drawbacks of measuring θ_{FC_INTACT} include added time and difficulty of sample collection and shipment of intact cores, as well as limited availability of laboratory analysis (at the time of publication, the authors were only able to locate one University laboratory to measure θ_{FC_INTACT}). Given this study's clear findings that θ_{FC_REPACK} does not respond to soil health management but that θ_{FC_INTACT} does, other laboratories may wish to provide θ_{FC_INTACT} analysis in the future. However, because of its current limited availability, θ_{FC_INTACT} is likely not a preferable indicator for projects looking to measure changes in soil health in general but is ideal for studies that assess changes in water retention due to changes in soil health management.

Bulk density, WSA, and SOC also responded to multiple management practices making them suitable to measure soil health though, unlike θ_{FC_INTACT}, they are not direct measures of soil hydraulic function. Soil organic C is meaningful because it is proximal to stakeholder values for those who wish to store more C in their soils, though our SOC measurements extend to 15 cm and a deeper measurement of C stock would be needed to address marketable SOC. As well, samples used to determine SOC and WSA can be composited (bulked) as opposed to θ_{FC_INTACT}, which cannot. Compositing can reduce shipping and analysis costs while supporting a larger spatial scale than an individual measurement. Feasibility of compositing D_b samples is somewhat in between that of SOC and θ_{FC_INTACT} in that the sample is initially obtained intact, but multiple cores may be combined into a single sample for analysis. Measures of D_b are especially relevant when considering compaction and are needed for calculation of both C stock and volumetric water contents, making D_b a key soil measurement as well as an indicator of changes in soil health. Sampling efforts designed to measure soil C stocks would therefore have both SOC and D_b as indirect indicators of soil hydraulic function and might not see additional benefit of adding θ_{FC_INTACT} if they wish only to know whether soil hydraulic function is improving but do not need information about water retention specifically. Least proximal to stakeholder values is aggregate stability (measured as WSA in this study), but it represents changes in soil structure that we expect to occur when soil hydraulic function improves. Studies that aim to assess surface sealing, crusting, or erodibility may particularly benefit from aggregate stability measurements (Amézketa, 1999). As well, sampling for aggregate stability can be done on composite samples and is quicker and less difficult than either K_S or θ_{FC_INTACT}.

Besides the effect of management on indicators across all NAPESHM sites, an additional component of indicator selection is the dependence of the response of the indicator to management on soil properties and climate. The response of θ_{FC_REPACK}, D_b, and WSA to reduced tillage were significantly related to inherent and climate variables. Indicators of soil health that that have a response to management that is correlated with inherent and climatic variables will have inconsistent response to management across regions and soils. Conversely, indicators of soil health that have a response to management that is independent of inherent and climatic variables will have more consistent response to management across soils and regions. Because changes in SOC and θ_{FC_INTACT} due to management were not significantly related to soil inherent and climates variables, they may be more robust indicator across many soils and climates.

Our last consideration for indicator selection was the correlation among indicators. If two indicators respond in the same way to management, this may allow an indicator that is indirect or less proximal to be substituted for a direct or more proximal indicator. This would be desirable if the substituted indicator is easier to measure or more affordable. For example, the response of SOC to reduced tillage explained a quarter of the variance in the response of θ_{FC_INTACT} to reduced tillage (had a correlation of .5; Figure 5c). Depending on the goals of the investigator and stakeholders, this might be sufficient evidence that reduced tillage had the desired effect on field capacity.

It is known that indicators of soil hydraulic function can vary a great deal within seasons and overtime (Strudley et al., 2008; van Es et al., 1999). Because our study considered one-time measurements on long-term studies, our findings may not apply to situations where indicators are measured over time or in newly established treatments.

4 | CONCLUSIONS

The NAPESHM project has enabled our selection of indicators of soil hydraulic function that are most useful for detecting changes in soil health due to management. Field capacity measured on intact cores was the best indicator of soil hydrologic function because it responded to management, is a direct measure of soil hydraulic function, is proximal to stakeholder values, and its response to management was not significantly influenced by inherent and climatic variables. Other useful indicators are D_b, SOC, and WSA, which were less direct measures of soil hydraulic function but do respond to management and may be practical in situations in which measuring θ_{FC_INTACT} is not. Choosing the best indicator for a particular study also depends greatly on study goals; for example, a focus on erodibility may make WSA the most preferred indicator and a focus on compaction would make D_b more appropriate.

The response of θ_{FC_INTACT} and SOC to reduced tillage did not depend on soil inherent and climatic variables, but the response of WSA and D_b did. Therefore, θ_{FC_INTACT} and SOC may be better choices for efforts that look to detect changes across many soils and environments. Because of low replications, K_S measured in this study was not interpretable. The remaining two indicators, θ_{FC_REPACK} and θ_{PWP}, were primarily driven by inherent and climatic variables, not management, and so they are not suitable indicators of soil health. Overall, identifying suitable indicators of soil hydraulic function, irrespective of climate and inherent soil properties are important for teasing apart how management drives soil health and affects sustainable soil resource management.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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