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ABSTRACT

Aggregate stability is a commonly used indicator of soil health because improvements in aggregate stability are related to reduced erodibility and improved soil–water dynamics. During the past 80 to 90 years, numerous methods have been developed to assess aggregate stability. Limited comparisons among the methods have resulted in varied magnitudes of response to soil health management practices and varied influences of inherent soil properties and climate. It is not clear whether selection of a specific method creates any advantage to the investigator. This study assessed four commonly used methods of measuring aggregate stability using data

Organic amendments
Indicators

collected as part of the North American Project to Evaluate Soil Health Measurements. The methods included water stable aggregates using the Cornell Rainfall Simulator (WSA_{CASH}), wet sieved water stable aggregates (WSA_{ARS}), slaking captured and adapted from SLAKES smart-phone image recognition software ($STAB_{10}$), and the mean weight diameter of water stable aggregates (MWD). Influence of climate and inherent soil properties at the continental scale were analyzed in addition to method responses to rotation diversity, cash crop count, residue management, organic nutrient amendments, cover crops, and tillage. The four methods were moderately correlated with each other. All methods were sensitive to differences in climate and inherent soil properties between sites, although to different degrees. None measured significant effects from rotation diversity or crop count, but all methods detected significant increases in aggregate stability resulting from reduced tillage. Significant increases or positive trends were observed for all methods in relation to cover cropping, increased residue retention, and organic amendments, except for $STAB_{10}$, which expressed a slightly negative response to organic amendments. Considering these results, no single method was clearly superior and all four are viable options for measuring aggregate stability. Therefore, secondary considerations (e.g., cost, method availability, increased sensitivity to a specific management practice, or minimal within-treatment variability) driven by the needs of the investigator, should determine the most suitable method.

1. Introduction

Soil structure is the backbone of a soil's ability to support processes vital to the health and productivity of plants, animals, and ecosystems. Soil structural units, or aggregates, form when fresh organic matter is decomposed by macrofauna and transformed by microbial community members into binding agents between mineral soil particles (Guhra et al., 2022; Jouquet et al., 2006). Work from Six et al. (2000) has provided evidence that over time, stable microaggregates form within macroaggregates, further enabling the development of soil structure; macroaggregates eventually bind into peds (several mm or even cm). The arrangement and stability of these structural units govern water and gas flow through soil, influencing soil microbial community members' ability to transform organic matter and cycle nutrients (Finn et al., 2017). Because of the role of soil structure in multiple soil functions, Dexter (1988) defined good soil structure as "one where all the hierarchical orders are well-developed and are stable against the actions of water and external mechanical stresses." Measuring the arrangement and stability of soil structure throughout the soil profile is time consuming and difficult, but an accepted indicator of soil structure is the ability of macroaggregates to resist dispersion, often referred to as aggregate stability (Amézketa, 2008).

Aggregate stability is generally quantified as the fraction of aggregates remaining after exposure to destabilizing stressors (Angers and Carter, 2020). The measure is a valuable indicator of soil health because it is conceptually linked to soil hydrologic function (Arshad and Coen, 1992; Hortensius and Welling, 2008; Moncada et al., 2015) and empirically linked to reduced erodibility (Barthès and Roose, 2002; Bryan, 1968; Coote et al., 1988; Elwell, 1986; Miller and Baharuddin, 1986) and increased infiltration (Miller and Baharuddin, 1986; Shainberg et al., 1992), as well as to agronomic function (root development, seedling emergence, etc.) (Angers and Caron, 1998; Gallardo-Carrera et al., 2007). These findings have led to the development of several methods to quantify aggregate stability with some currently incorporated in soil health tests (Andrews et al., 2004; Moebius-Clune et al., 2016). Although each method has been shown to be sensitive to soil health management systems (Bagnall and Morgan, 2021; Li et al., 2019; Moebius-Clune et al., 2008), limited comparisons between methods have found that the magnitude of response to changes in management varies greatly with method (Almajmaie et al., 2017; Flynn et al., 2020; Moncada et al., 2015; Obalum et al., 2019; Van Eerd et al., 2018). Understanding each method's sensitivity to changes in management practices is key to providing appropriate interpretations of the measurement in relation to soil health.

Differences in indicator sensitivity to management likely stem from the various methods assessing different diameters and masses of aggregates and applying different types and magnitudes of disruptive forces (Table 1) (Almajmaie et al., 2017; Amézketa, 2008; Deviren Saygin et al., 2012; Moncada et al., 2015). These differences may affect how inherent conditions contribute to measures of aggregate stability. For example, the relationship between clay content and aggregate stability is disputed in literature. Some studies, conducted in croplands located in arid to subhumid climates show that aggregate stability increases with clay content (Boix-Fayos et al., 2001; Kemper and Koch, 1966), while others report that aggregates, collected from native and cropland soils from a wide range of climates (300-mm to 1500-mm annual precipitation) were less stable in high clay soils (Fajardo et al., 2016; Ternan et al., 1996). Furthermore, external factors, such as climate, may indirectly influence aggregate stability through differential organic carbon formation at the continental scale (Nunes et al., 2020). Organic compounds are known to form organo-mineral complexes in soil. However, contradictory results exist among correlations between aggregate stability and organic matter (Amézketa, 2008). Determining how inherent soil properties and climate influence different measures of aggregate stability will enhance interpretability of the measures across geographic regions.

The goal of the present study was to evaluate the influence of inherent soil properties, climate, and agricultural management on four commonly used measures of aggregate stability recorded on samples collected from long-term research stations across primary agricultural areas in North America. These measures included the Cornell Rainfall Simulator (Moebius-Clune et al., 2016), wet sieve Procedure (Kemper and Rosenau, 1986; Yoder, 1936), the SLAKES smart phone app (Fajardo et al., 2016), and the mean weight diameter of water stable aggregates (Franzluebbers et al., 2000). The wet sieve procedure and mean weight diameter of water stable aggregates both utilize mechanical forces from standardized movements to induce slaking of unstable aggregates. The Cornell Rainfall simulator method mimics the impact of raindrops on aggregates, while the SLAKES smart phone app measures the slaking of

Table 1
Summary of aggregate stability methods used in the North American Project to Evaluate Soil Health Measurements.

	Cornell Rainfall Simulator	Slaking Image Analysis	Wet Sieve Procedure	Mean Weight Diameter
Overview	Slaking by water impact	10-min change in slaking via image analysis	Wet sieving	Wet sieving, multiple sieve sizes
Aggregate Diameter	0.25 to 2.0 mm	3 to 10 mm	1 to 2 mm	< 4.75 mm
Sieve Mesh Size(s)	0.25 mm	NA[§]	0.25 mm	1.0, 0.25, 0.05 mm
Sample Mass	20 g	~8 g	4 g	19 g
Output Unit	% water stable aggregates	10 min ratio of aggregate image areas	% water stable aggregates	mean weight diameter, mm
Abbreviation	WSA_{CASH}	$STAB_{10}$	WSA_{ARS}	MWD

[§] No sieves were used in the $STAB_{10}$ methodology.

aggregates following a 10-minute submersion in water. Our first objective was to evaluate the influence of inherent soil properties and climate across the North American Continent on the four methods. Secondly, method sensitivity to long-term adoption of soil health management practices was investigated. We explored how inherent soil property relationships influence changes in aggregate stability due to tillage. Finally, aggregate stability responses to tillage in relation to changes in other common soil health indicators was investigated.

2. Methods

2.1. Sample collection

Data used in these analyses were collected as part of the North American Project to Evaluate Soil Health Measurements. A more detailed description of the project can be found in Norris et al. (2020). The project sampled 2,012 experimental units from 688 replicated treatments located at 124 long-term experimental agricultural research sites across the United States, Mexico, and Canada. Five-hundred sixty-eight treatments contained at least ten years of continuous management and the remaining 120 treatments contained between six and ten years of continuous management. Sites were chosen based on the presence of treatments designed to test management effects of tillage, cover crops, crop rotation, residue retention, and nutrient amendments.

Sites were sampled in spring of 2019 prior to spring chemical or physical management practices. For each treatment, a five-year detailed management history, representative of the long-term management history (>10-years) was collected. Experimental units were collected using a sharpshooter shovel and soil knife. The sharpshooter shovel was used to remove 15-cm deep plugs from four to six representative locations within a given experimental unit (either plots or fields that represent one replication of a treatment). At each hole, three uniform soil knife slices (4-cm wide by 1.5-cm thick) were collected to a depth of 15-cm from the three undisturbed sides of the hole. All slices of soil for each experimental unit were composited and homogenized by hand mixing with care to maintain as much natural aggregation as possible. Composited samples were divided into subsamples of various weights appropriate for each analysis and mailed to laboratories. In addition to the composite soil sample, four intact 7.6-cm diameter soil cores were collected to a depth of 7.6 cm in each experimental unit and maintained intact using a plastic sleeve. Two of the four cores were kept intact for analysis, while the remaining two were combined into a bag. The composite cores and intact cores were analyzed for bulk density, while only intact cores were analyzed for available water holding capacity (results presented elsewhere, (Bagnall et al., 2022)).

2.2. Laboratory measurements

Hand-homogenized soil from knife slices collected from each experimental unit was sent to the Soil Water and Environmental Lab at Ohio State University for measurement of pH, particle size distribution, total carbon, inorganic carbon, and effective cation exchange capacity. Particle size analyses were performed using the pipette method and sands were wet sieved (Gee and Or, 2018). Soil pH was measured using a 1:2 soil:water slurry with a pH electrode. Total carbon was measured by dry combustion (Nelson and Sommers, 2015). Inorganic carbon was measured using the Chittick gasometric calcimeter[1] (St. Louis, MO, USA). Soil organic carbon was calculated as the difference between total organic carbon and inorganic carbon (Dreimanis, 1962). Potential carbon mineralization was measured as an accumulation of CO_2-C following rewetting to an estimated 50 % water filled pore space and a 24-hour incubation period (Zibilske, 2018). Sodium, magnesium, potassium, and calcium ion concentrations were extracted with Mehlich-3 extractants (Mehlich, 1984) and quantified using inductively coupled plasma spectrometry (Thomas, 2015). Ion concentrations were transformed to molar equivalent charges and summed to calculate effective cation exchange capacity. Ratios of individual ions were computed by dividing molar equivalent charges by effective cation exchange capacity.

Soil from the four intact cores were shipped to the Cornell Soil Health Laboratory (Ithaca, NY) for bulk density calculations. For experimental units with less than 2 % coarse fragments by mass (determined during particle size analysis preparations), bulk density was calculated as the mean value of all four cores. For experimental units with more than 2 % coarse fragments by mass, fine-earth fraction bulk density was calculated as the mean of the two composited cores, following removal of coarse fragments, with adjustments correcting for mass and volume of the coarse fragments.

For aggregate stability analyses, composite soil from each experimental unit was sent to three labs, the Cornell Soil Health Laboratory (Ithaca, NY), the Ohio State University's Soil, Water, and Environmental Laboratory (Columbus, OH), and the Texas A&M AgriLife Research Soil Characterization Laboratory (College Station, TX). Four aggregate stability methods were employed as follows: the Cornell Rainfall Simulator method (commonly referred to as the "Cornell wet aggregate stability test") (Moebius-Clune et al., 2016) was performed at Cornell; both the Wet Sieve Procedure (commonly referred to the "wet aggregate stability test") (Kemper and Rosenau, 1986) and water stable aggregate mean weight diameter (Franzluebbers et al., 2000) were performed at Ohio State; and image recognition using the SLAKES smart phone application was employed at Texas A&M (Fajardo et al., 2016). An overview of each procedure can be found in Table 1. Aggregate stability indicator, climate, inherent soil properties, and measured soil metric descriptive statistics are located in Supplementary Table 1.

The Cornell Rainfall Simulator method examines the force of water droplets on air-dried aggregates. Aggregates used in the method were collected by initially passing air-dried soil through an 8-mm sieve. Approximately 250 g of this soil was placed onto a stack of two sieves (2-mm and 0.25-mm) and a catch pan. This assembly was shaken for 15 s on a Tyler Sieve shaker (Moebius-Clune et al., 2016). The aggregates captured on the 0.25-mm sieve were collected. The Cornell rainfall simulator device applied deionized water droplets with a total force of 1.9 J to the soil aggregates placed on a 0.25-mm mesh sieve for 5 min. Soil that passed through the sieve during the simulated rainfall was collected on filter paper beneath the sieve and weighed. Aggregates remaining on the sieve were crushed, separating sand from stable aggregate components, so only sand particles remain on the sieve. Sand particles and unstable aggregates were dried and weighed. Water stable aggregates (WSA_{CASH}) were calculated as percent of the total soil mass as follows:

$$WSA_{CASH} = \frac{dryinitial - sand - unstable}{dryinitial - sand} x100 \quad [1]$$

Aggregate dispersion was measured using image recognition software via the SLAKES free smart phone application (Fajardo et al., 2016; SLAKES, 2018). Three non-sieved, air-dried aggregates, measuring approximately 3 to 10-mm in diameter, were placed in an empty petri dish positioned on top of white paper. The smart phone was suspended above the petri dish at a height such that the entire petri dish was visible in the view of the phone camera. Two light sources were directed toward the petri dish in a position that eliminated shadows within the field of view on the phone. A referenced image (A_0) of the aggregates was captured, and then aggregates were transferred to a petri dish filled with water. Care was taken to place aggregates in the petri dish with water in the same relative location and orientation as in the reference image. As the aggregates dispersed, SLAKES software recorded the area of each aggregate continuously for 10 min. At the conclusion of the 10-min dispersion, the area of each aggregate was recorded (A_{600}). The time

[1] Names given are to provide specific information and do not constitute endorsement by the authors over other entities that may be equally suitable.

stamp and aggregate area data in the SLAKES application were exported to an Excel file where a 10-min stability value ($STAB_{10}$) was calculated by dividing the initial area (A_0) of the reference image by the final area at 600 s, or 10 min, (A_{600}) (Eq. 4).

$$STAB_{10} = \frac{A_0}{A_{600}} \quad [2]$$

The image-recognized aggregate area wavered considerably during the first five seconds for some samples. This was caused by improper recognition of soil aggregates due to shadowing or rapid dispersion. As a result, several 10-min stability values were>1. To obtain the most accurate quantification of 10-min stability, the value for A_0 was reselected using the minimum aggregate area within the first five seconds and A_{600} was reselected as the maximum aggregate area within the final five seconds. For $STAB_{10}$, nine $STAB_{10}$ values were used from three petri dishes containing three aggregates in each dish. Nine 10-min stability values were obtained for each experimental unit by measuring dispersion of three aggregates in three separate petri dishes. The $STAB_{10}$ aggregate stability reported for each experimental unit represents the geometric mean of $STAB_{10}$ from the nine aggregates.

The wet sieve procedure described in Kemper and Rosenau (1986) evaluated the slaking of aggregates subject to oscillation in water. Aggregates used in the method were prepared by gently crumbling field-moist soil without causing compression and oven-dried at 55 °C for 2 to 3 days. The oven-dried soil was then passed through a 4.75-mm sieve by tapping with a mallet to apply the minimum force necessary to cause it to pass through the sieve. Approximately 4 g of air-dried aggregates 1 to 2-mm in diameter were placed on a 0.25-mm mesh sieve. The sieve was oscillated in deionized water for 2 min. Aggregates remaining on top of the sieve were then oscillated in a dispersing solution (2 g $(NaPO_3)_6$ and 0.45 g Na_2CO_3 dissolved in 1 L of deionized water) for 5 min to separate the stable aggregates from sand particles. A rubber-tipped rod was used to break any aggregates remaining on the sieve. The contents of the dispersing residue container were then dried and weighed. Aggregate stability, via the wet sieve procedure (WSA_{ARS}), was calculated and expressed as percent water-stable aggregates using the following equation:

$$WSA_{ARS} = \frac{(stable - dispersalresidue)}{(unstable + stable - dispersalresidue)} \times 100. \quad [3]$$

Mean Weight Diameter (MWD) was calculated as the weighted mean of each aggregate size class and their respective relative weight proportions. Aggregates used in this method were prepared in the same manners as those used in the WSA_{ARS} method. To calculate MWD, 19 g of the prepared aggregates were placed on a stack of sieves with mesh sizes of 1.0 and 0.25-mm and oscillated in water for 10 min. Aggregates passing through the 0.25-mm mesh sieve were transferred to a 0.053-mm mesh sieve and flushed with water. Aggregates remaining on each sieve were dried and weighed for determination of MWD using the following equation:

$$MWD = \sum_{i=1}^{n} \vec{x}_i w_i; \quad [4]$$

where $\vec{x}_i$ is the mean diameter of the sieve size the wet stable aggregates did not pass through, and w_i is the ratio of stable aggregate weight to total weight for each size portion, and i ranges from 1 to n reflecting an index of the number of mesh sizes used.

2.3. Statistical approach

Data analysis was performed in RStudio Version 1.2.5001 (R Core Team, 2020) with base R functions and statistical significance determined at $p < 0.05$, unless noted otherwise. Distributions of the aggregate stability indicators were explored with histograms. Indicators were log transformed based on distributions. Relationships between the indicators were characterized using Pearson's correlation coefficients. Variability of the four aggregate stability indicators was explored in treatments containing at least three experimental units. Random intercept models were used to partition each indicator's total variance using restricted maximum likelihood estimation in the lme4 package (Bates et al., 2015). Three sources of variance were calculated: 1) variance among site means; 2) variance among treatment means nested within site; and 3) variance among individual replicates nested within treatment. The estimates from the models are reported as the percent of total variance that can be attributed to the respective source. Relationships between aggregate stability indicators and inherent site properties were explored using multiple regression models using site means for all variables. Inherent properties included sand content, clay content, pH, temperature, and precipitation. Temperature and precipitation variables consisted of 10-year mean annual temperature and precipitation for each site. Daily weather data were collected from Daymet (Thornton et al., 2016) from 2009 to 2019 to compute 10-year means.

To determine the sensitivity of aggregate stability indicators to management, treatment comparisons, within any one site, were confined to those that differed by only one soil health management practice. Soil health promoting practices included rotation diversity, crop count, residue management, organic nutrient sources, cover crops, and reduced physical disturbance. Rotation diversity compared rotations with only cereal grains to rotations with additional types of crops. Additional types of crops mainly consisted of legumes, but also included canola (*Brassica napus*), safflower (*Carthamus tinctorius*), and cotton (*Gossypium hirsutum*). Crop count compared monoculture treatments to treatments with at least two different cash crops. Residue management compared treatments with identical management other than the amount of biomass removed following grain harvest. Organic nutrient treatments were compared against treatments receiving inorganic nitrogen and/or phosphorus commercial fertilizers. Organic nutrients included biosolids, compost, herbaceous materials, and manure. Treatments that included a cover crop in at least one year of the cropping system rotation were compared to treatments not containing cover crops. A cover crop was defined as a crop which was planted and terminated within a year by herbicides, fall frost, or tillage, and the biomass was not harvested or removed. Sites with varying physical soil disturbances were classified using the standard tillage intensity rating (STIR) (USDA-NRCS, 2008) value for the most disruptive implement for each treatment. Paired disturbance treatments were selected if management was the same except tillage, and therefore different STIR values.

A meta-analysis approach was used to compare the response of aggregate stability indicators to long-term adoption of soil health management practices of this investigation. The rma.mv function in the metafor R package (Viechtbauer, 2010) was used to fit a meta-analytic model to predict log response ratios between treatments with only one different management practice. The log response ratios were the natural log of the ratio between a soil health management practice and treatment not containing the management practice, controlling for site as a random variable. Aggregate stability indicators were determined to have a significant response to each individual soil health management practice if the 95 % confidence interval, calculated by the meta-analytic model, did not contain zero. Response ratios and calculated confidence intervals were transformed to percent change for clear communication of relative change due to management.

The influence of inherent soil properties and climate on aggregate stability indicator response to tillage was explored by fitting multiple linear regressions to tillage log response ratios, averaged by site. Only models for tillage were fit because the other management practices had too few sites. Predictors included site average clay and sand contents, pH, mean annual precipitation, and mean annual temperature, along with their two-way interactions. The relationship between changes in aggregate stability indicators due to tillage and changes in common soil health indicators due to tillage were explored by fitting linear regressions to tillage log response ratios. Predictors were soil organic carbon, potential carbon mineralization, and bulk density log response ratios. Response ratios were transformed to percent change to ease visual interpretation of the relationships. Additionally, the effects of management practices on concentrations of sodium ions were explored with paired *t*-test performed on paired treatment means used to calculate log response ratios.

3. Results

3.1. Distribution of indicators

All four methods of measuring of aggregate stability were log normally distributed (Fig. 1). Each method represented a wide range of aggregation from very stable to unstable. The methods were moderately correlated with each other with Pearson's correlation coefficient ranging from 0.45 to 0.69. The strongest correlation was between WSA_{CASH} and WSA_{ARS} and weakest between $STAB_{10}$ and MWD (Fig. 1). In general, $STAB_{10}$ was least correlated with the others. Random intercept model results for all treatments with at least three experimental units identified variance among sites accounted for the majority of variance for all indicators, followed by variance among treatments and within treatments, respectively (Table 2). The within treatment variation was greatest in $STAB_{10}$, followed by WSA_{CASH}, MWD, and WSA_{ARS} (Fig. 2).

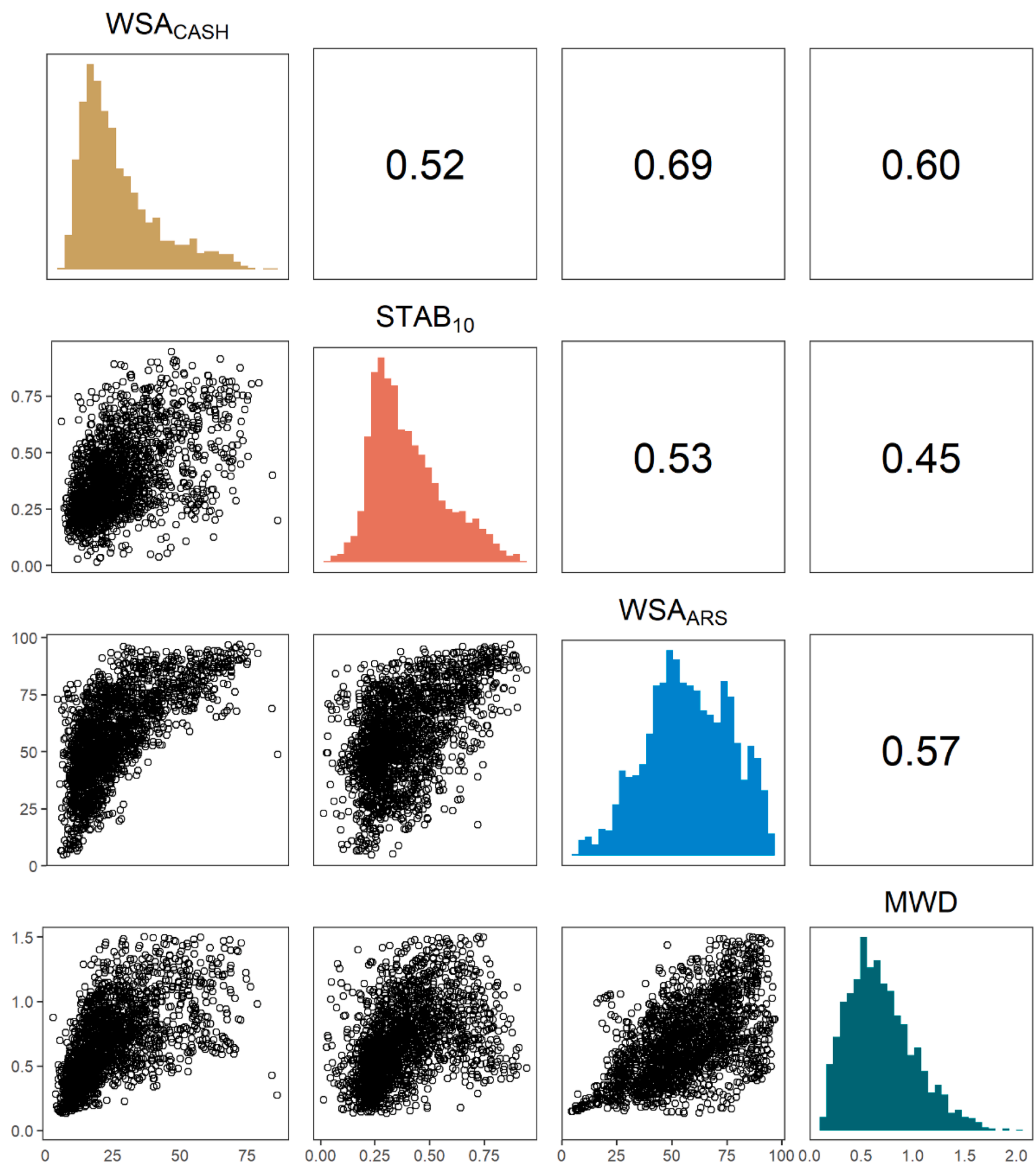

Fig. 1. Aggregate stability indicator correlation matrix. The scatter plots of the bottom left panels correspond to Pearson's correlation coefficients located in the top right panels. The diagonal illustrates distributions of the four indicators. WSA_{CASH} is water stable aggregates following simulated rainfall; $STAB_{10}$ is 10-minute change in aggregate stability; WSA_{ARS} is wet sieved water stable aggregates; and MWD is mean weight diameter.

Table 2
Percent of total variance partitioned among site means, among treatment means nested within site, and among individual replicates nested within treatment. WSA_{CASH} is water stable aggregates following simulated rainfall; $STAB_{10}$ is 10-minute change in aggregate stability; WSA_{ARS} is wet sieved water stable aggregates; and MWD is mean weight diameter.

	Percent of Total Variance		
	Among sites	Among treatments	Within treatments
WSA_{CASH}	64	23	13
$STAB_{10}$	77	12	11
WSA_{ARS}	59	33	8
MWD	68	22	10

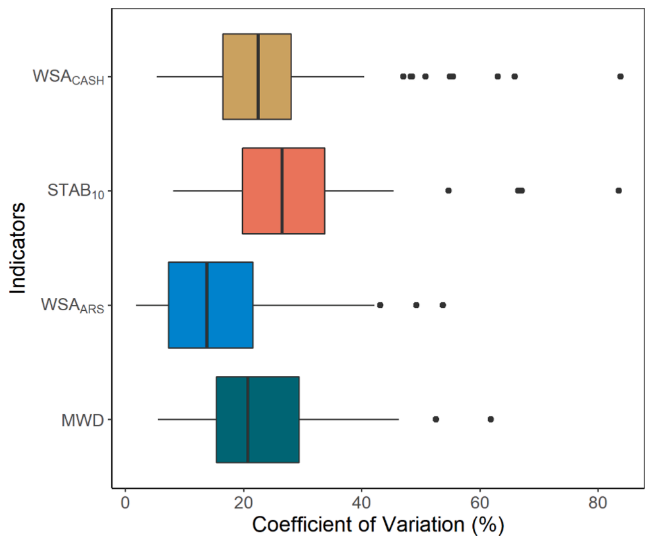

Fig. 2. Boxplots of coefficients of variation for aggregate stability indicators within treatments. WSA_{CASH} is water stable aggregates following simulated rainfall; $STAB_{10}$ is 10-minute change in aggregate stability; WSA_{ARS} is wet sieved water stable aggregates; and MWD is mean weight diameter.

3.2. Climate and inherent soil property influence

Variance among sites accounted for 59 to 77 % of total variance (Table 2). The adjusted R^2 for multiple linear regression models used to predict aggregate stability indicators with inherent characteristics ranged from 0.05 for MWD to 0.37 for $STAB_{10}$ (Table 3). Every variable was significant in the WSA_{CASH} model, which was the only model where clay content and pH were significant. Precipitation was a significant predictor in all four models. Additionally, only climatic variables (temperature and precipitation) were significant in predicting WSA_{ARS}. Furthermore, sand was a significant predictor in modeling $STAB_{10}$ and WSA_{CASH}.

3.3. Response to management

Treatment means nested within sites accounted for between 12 and 33 % of total variance (Table 2). Based on the meta-analysis, the aggregate stability indicators were sensitive to some soil health management practices, but not all. Increased rotation diversity or crop counts did not significantly increase any of the indicators (Fig. 3a, 3b). Conversely, reducing tillage significantly increased all four aggregate stability indicators (Fig. 3f). Mean increases in the indicators ranged from 10 to 18 %, with WSA_{CASH} having the greatest mean response to reductions in tillage. Residue retention significantly increased WSA_{CASH}, $STAB_{10}$, and MWD (Fig. 3c). Organic nutrient additions significantly increased only WSA_{ARS} and MWD (Fig. 3d), while implementing cover crops significantly increased WSA_{CASH} and $STAB_{10}$ (Fig. 3e). Although WSA_{ARS} and MWD did not significantly increase with cover crops, the measures trended similarly to the other indicators.

3.4. Interactions between inherent soil properties and climate variables on response of indicators to tillage practices

Two of the four aggregate stability indicators, WSA_{CASH} and WSA_{ARS}, had significant multiple linear regression models when the response of aggregate stability to tillage was predicted by inherent and climatic variables. Predictors included site average clay and sand contents, pH, precipitation, and temperature, along with their two-way interactions. The model for WSA_{CASH} had an R^2 of 0.25 and the model for WSA_{ARS} had an R^2 of 0.28. For WSA_{CASH}, two interaction terms were significant: 1) the interaction of temperature and precipitation; and 2) the interaction of sand content by clay content. Interaction plots were used to display the conditional effect (accounting for all model predictors) of each significant interaction term on the response of the aggregate stability indicator to tillage by plotting one predictor from the interaction as a continuous variable on the x-axis and the second predictor variable as three regression lines (Fig. 4). The regression lines in Fig. 4 represent the mean of that variable, one standard deviation below the mean, and one standard deviation above the mean. Soils in this study with greater clay content had greater increases in WSA_{CASH} due to decreased tillage, but soils with little sand were exceptions (Fig. 4a). As well, WSA_{CASH} had lesser responses to decreased tillage either in dry, cool climates or in hot, wet climates (Fig. 4b). The largest response of WSA_{CASH} to reduced tillage was in sites with low temperature and high precipitation. For WSA_{ARS}, only the interaction between sand and temperature was significant. The interaction indicated that in general, WSA_{ARS} has less of a response to reduced tillage when mean annual temperature is greater, except in very sandy soils (sand $>$ 58 %).

3.5. Aggregate stability indicator response to tillage in relation to soil health metrics

Linear regressions between log response ratios of soil organic carbon to tillage and log response ratios of aggregate stability to tillage revealed significant, positive relationships ($p < 0.001$) for all four aggregate stability indicators (Fig. 5a). The positive relationships indicate

Table 3
Adjusted R^2 for multiple regression models and significant predictors for site means of aggregate stability indicators. Numbers in parentheses are p-values associated with each measurement. Bold font indicates $p > 0.05$. All indicators were log transformed. WSA_{CASH} is water stable aggregates following simulated rainfall; $STAB_{10}$ is 10-minute change in aggregate stability; WSA_{ARS} is wet sieved water stable aggregates; and MWD is mean weight diameter.

Aggregate Stability Indicator	Sand	Clay	pH	Temperature	Precipitation	Adjusted R^2
WSA_{CASH}	+[§] **(3×10^{-5})**	+ **(1×10^{-3})**	[β] **(0.04)**	- **(5×10^{-3})**	+ **(0.01)**	0.17
$STAB_{10}$	+ **(4×10^{-5})**	- (0.39)	- (0.37)	- (0.051)	+ **(1×10^{-3})**	0.37
WSA_{ARS}	+ (0.072)	+ (0.84)	- (0.43)	- **(8×10^{-3})**	+ **(1×10^{-3})**	0.15
MWD	+ (0.089)	+ (0.071)	- (0.21)	- (0.14)	+ (0.021)	0.05

[§] Predictor contained a positive slope.
[β] Predictor contained a negative slope.

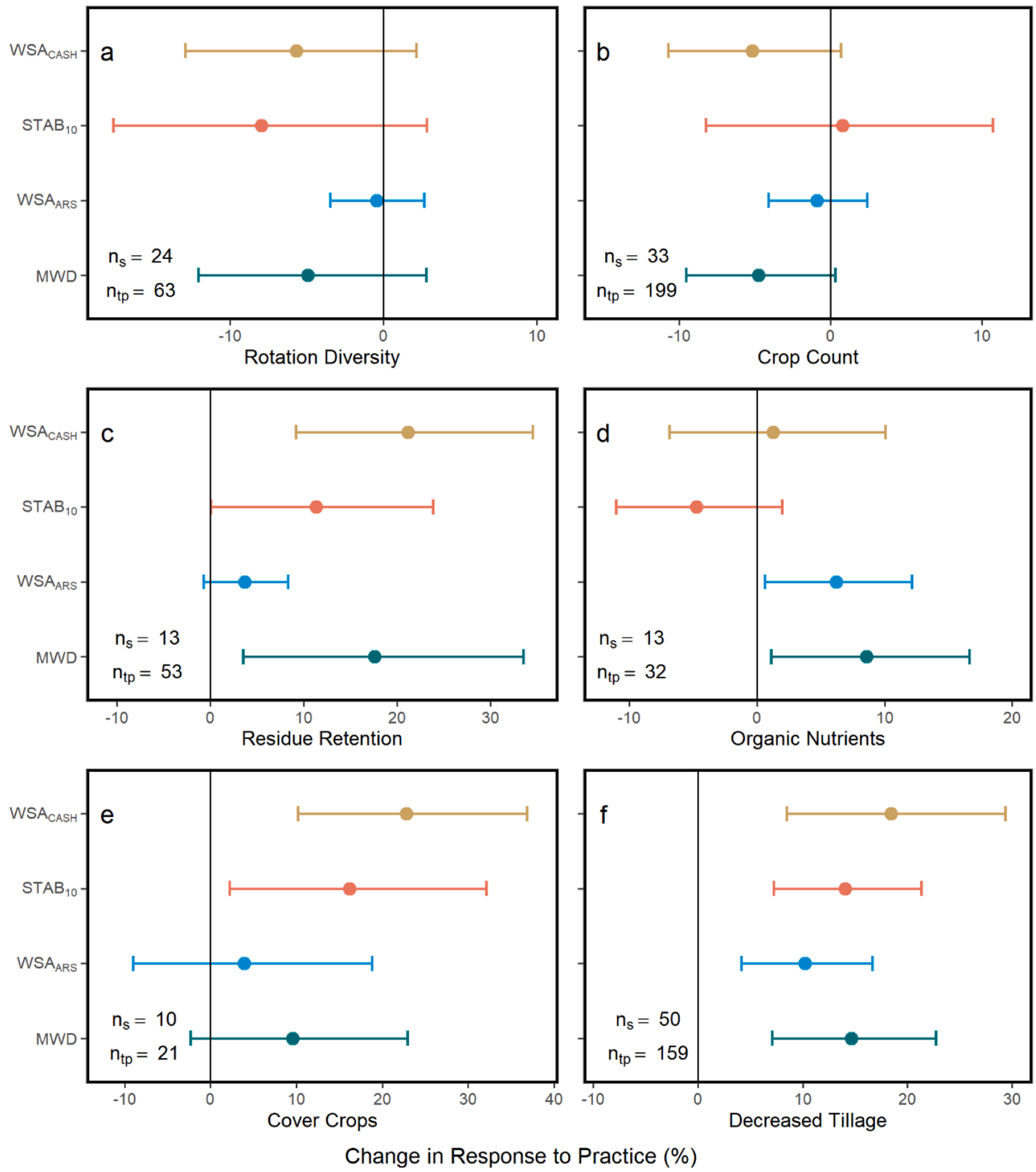

Fig. 3. Response ratios for aggregate stability indicators by management practice. Dots are means and bars represent 95% confidence limits. WSA_{CASH} is water stable aggregates following simulated rainfall; $STAB_{10}$ is 10-minute change in aggregate stability; WSA_{ARS} is wet sieved water stable aggregates; and MWD is mean weight diameter. n_s is the number of sites included in the analysis, and n_{tp} is the number of treatment pairs included in the analysis.

increases soil organic carbon, resulting from reduced tillage, are correlated with increases in aggregate stability indicators. Linear regression coefficients between the log response ratios ranged from $r^2 = 0.12$ for $STAB_{10}$ to $r^2 = 0.41$ for WSA_{CASH}. Similarly, linear regressions between log response ratios for potential carbon mineralization and aggregate stability to tillage were all positively significant ($p < 0.001$), with regression coefficients ranging from $r^2 = 0.09$ for $STAB_{10}$ to $r^2 = 0.23$ for WSA_{CASH} (Fig. 5b). Though changes in soil organic carbon and potential carbon mineralization reflected changes in every aggregate stability indicator due to tillage, only changes in $STAB_{10}$ values were significantly related to changes in bulk density ($p = 0.02$), with $r^2 = 0.02$ (Fig. 5c).

4. Discussion

4.1. Influence of inherent soil properties and climate

The effect of inherent soil properties and climate on soil health indicators must be considered prior to indicator comparison across space. The magnitude of influence of the selected inherent and climatic variables varied among the four aggregate stability indicators, from little influence on MWD to moderately influence on $STAB_{10}$. Although the magnitude of influence differed among the indicators, all four indicators had a significant, positive relationship with mean annual precipitation. While most prior studies analyzing aggregate stability were performed in a single location or region, Cerdà (2000) & Buchi et al., (2022) found regions with a greater precipitation demonstrated greater aggregate stability. Conversely, many studies have linked aggregate stability to soil organic carbon (Amézketa, 2008), which is influenced by precipitation at the continental scale (Nunes et al., 2020). Furthermore, WSA_{ARS} and WSA_{CASH} were negatively related to mean annual air temperature, which is also known to influence soil organic carbon at the continental scale (Nunes et al., 2020). Thus, the influences of air temperature and precipitation on aggregate stability are likely driven by changes in soil organic C (Liptzin et al., 2022), with cooler temperatures and greater precipitation being related to greater aggregate stability.

In addition to precipitation, sand content positively influenced

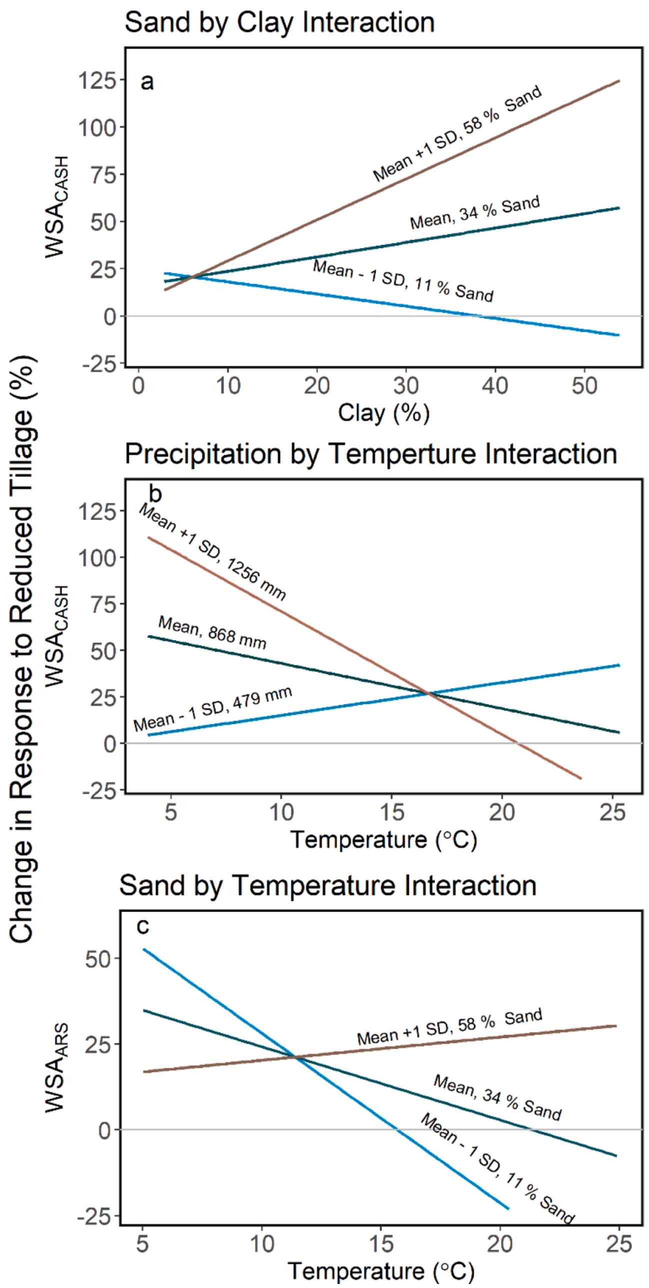

Fig. 4. Plots for conditional effects (accounting for all predictor variables in the model) of significant two-way interactions from multiple linear regressions. Multiple linear regressions predicted the response ratios of water stable aggregates following simulated rainfall (WSA_{CASH}) and wet sieved water stable aggregates (WSA_{ARS}) 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.

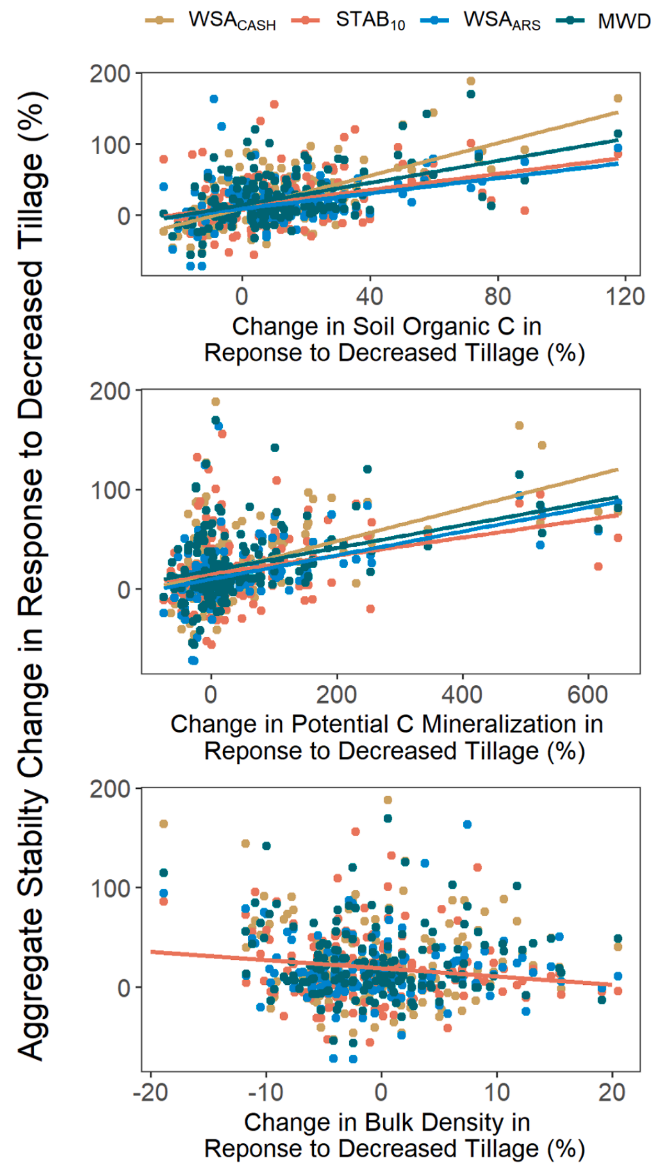

Fig. 5. Linear regressions (p-value < 0.001) between the percent differences in aggregate stability indicators in response to decreased tillage and A) percent difference in soil organic carbon in response to decreased tillage; B) percent difference in potential carbon mineralization in response to decreased tillage; and C) percent difference in bulk density in response to decreased tillage. MWD is mean weight diameter; WSA_{ARS} is wet sieved water stable aggregates; $STAB_{10}$ is 10-minute change in aggregate stability; and WSA_{CASH} is water stable aggregates following simulated rainfall.

$STAB_{10}$ and WSA_{CASH} measurements at the site level. The positive relationship of $STAB_{10}$ with sand may be attributed to sand particles quickly falling out of suspension following submersion of the aggregates in water, resulting in a smaller change in aggregate diameter. The positive influence of sand content on WSA_{CASH} measurements at the site level may be attributed to the way the procedure corrects for sand in the method. The procedure corrects for coarser sand particles by rinsing the stable aggregate fraction remaining after rainfall simulations through a 0.25 mm sieve (Moebius-Clune et al., 2016). However, soils with high fractions of fine and very fine sand (0.25 mm − 0.10 mm and 0.10 mm − 0.05 mm, respectively) are not corrected for with this method. The effect of texture is considered in the Comprehensive Assessment of Soil Health scoring function for WSA_{CASH}, where greater values of WSA_{CASH} in coarse soils are necessary to achieve a “good” or “very good” rating compared to fine and medium textured soils (Fine et al., 2017).

Only WSA_{CASH} had a significant, positive relationship with clay content at the site level. Sensitivity to clay content was also observed by Fine et al. (2017), where WSA_{CASH} was greater in fine-textured soils when compared to medium-textured soils. Additionally, prior studies have reported a range of influence of clay content on aggregate stability, including positive, negative, and negligible effects (Angers, 1998; Fajardo et al., 2016; Franzluebbers et al., 2000; Regelink et al., 2015). The variable sensitivity to inherent features likely arises from different indicator methodologies, where a range of aggregate sizes, forces applied, and metrics measured are observed. While certain inherent features are known to aid in building soil structure (e.g. clay particles forming organo-mineral complexes, clay particle flocculation in saline soils), it is important to note aggregate stability indicators, which are assessed on macroaggregates only, are proxies for understanding differences in soil structure (including microaggregates, macroaggregates, and larger soil structural units) resulting from changes in management. Furthermore, pH, clay, sand, temperature, and precipitation only predicted a small proportion of indicator variability at the site level, while random intercept model results indicated variance among sites accounted for most of the variation. This suggests that other, unmeasured, site-specific properties contributed to indicator variability between sites.

4.2. Response to management

A desired trait across all indicators of soil health is sensitivity to changes in agricultural management (Doran and Zeiss, 2000). Our study investigated the effect of six individual soil health management practices on aggregate stability indicators, including reduced tillage, cover cropping, organic nutrient amendments, reduced residue removal, extended crop rotations, and increased cropping system diversity. Most indicators were sensitive to reduced tillage, cover cropping, organic nutrient amendments, and reduced residue removal, but no indicator significantly changed in response to increased rotation diversity or crop counts. In fact, most indicator responses to increased rotation diversity and crop counts trended slightly negative. This response may partially be due to 25 % of the rotation diversity and crop count comparisons in this study were between continuous corn and corn-soybean rotations. Rotations that include legumes generally return less biomass to the soil compared to cereal grains and can lead to reductions in soil organic carbon (King and Blesh, 2018; West and Post, 2002), thus affecting aggregate stability (Amézketa, 2008). Although increasing cropping diversity did not lead to greater aggregate stability in this study, the management practice has been linked to other benefits, such as reductions in disease severity (Larkin et al., 2012; Latz et al., 2012).

All four indicators responded positively to residue retention, with significant increases in WSA_{CASH}, $STAB_{10}$, and MWD. These results complement prior studies assessing the effect of residue management on aggregate stability. A recent meta-analysis by Li et al. (2019) found residue retention significantly increased measurements similar to MWD and WSA_{ARS} in this study. Previous studies have also shown WSA_{CASH} to be sensitive to residue retention (Mochizuki et al., 2008; Moebius-Clune et al., 2008; Moebius et al., 2007). To date, no prior studies have analyzed the impact of residue removal on $STAB_{10}$. The consistent, positive response of all aggregate stability indicators in this study and prior studies suggests any of the methods can capture changes in soil structure resulting from differences in residue management, though WSA_{ARS} did not have a significant response in this study.

Indicator response to organic nutrient amendments varied the most out of all six management practices analyzed, with WSA_{ARS} and MWD significantly increasing, WSA_{CASH} slightly increasing, and $STAB_{10}$ slightly decreasing. The nutrient amendment management category mainly compared treatments receiving fresh or composted manure against those receiving only inorganic fertilizers. Although indicator responses were variable, the results aligned with findings from prior studies. A number of studies have found increases in WSA_{ARS} and MWD following compost, manure and straw additions (Bottinelli et al., 2017; Gerzabek et al., 1995; Karami et al., 2012; Wortmann and Shapiro, 2008). Few studies to date have assessed WSA_{CASH} in relation to organic additions and report variable results (Roper et al., 2017; van Es and Karlen, 2019). Furthermore, this study was the first to report $STAB_{10}$ results in relation to organic amendments. The slight, negative response of $STAB_{10}$ to organic nutrient amendments was the only occasion where the indicator response did not trend similarly to the other indicators. Paré et al., (1999) found slaking to be greater in aggregates from soils receiving fresh manure when compared to non-manured soils; however, overall proportions of water stable aggregates were still greater in manured soils. Organically amended soils in this study contained significantly greater proportions ($p < 0.05$, mean difference = 1.50×10^{-3}) of sodium ions when compared to their non-amended counterparts. The greater concentrations of sodium ions contained in the treatments and the larger aggregates used to measure $STAB_{10}$ may have both contributed to the increased slaking, which is considered the dominant force acting on the measurement.

The use of cover crops significantly increased WSA_{CASH} and $STAB_{10}$, while WSA_{ARS} and MWD trended towards positive responses. Numerous studies have investigated the effect of cover crops on aggregate stability. Most studies report significant increases in aggregate stability in at least one cover crop treatment (Antosh et al., 2020; Jokela et al., 2009; Liu et al., 2005; Steele et al., 2012; Wood and Bowman, 2021), while others found increases in all cover crop treatments (Mitchell et al., 2017; Villamil et al., 2006) or no cover crop treatments (Abdollahi and Munkholm, 2014; Idowu et al., 2009). The differing results from individual studies may be partially attributed to limited adoption periods (2 to 4 years) prior to sampling. There were only twenty-one long-term (average adoption period of fifteen years) cover crop treatment comparisons, located at ten sites, the fewest of any management comparisons in the study. There was also considerable variation in the types of cover crops used (grasses, legumes, brassicas), which is expected to have a differential impact on the quantity and quality of biomass additions and may have led to greater variation. The greater sensitivity of WSA_{CASH} and $STAB_{10}$ to cover crop implementation in this study may make these indicators more desirable for identifying significant differences in aggregate stability among cover crop treatments.

Reduced tillage was the only management practice where all four indicators detected significant, positive effects. These results agree with numerous studies that have found increases in aggregate stability in reduced tillage treatments across methods (Abid and Lal, 2008; Bagnall and Morgan, 2021; Bottinelli et al., 2017; Guo et al., 2020; Idowu et al., 2009; Kasper et al., 2009; Van Eerd et al., 2018; Weidhuner et al., 2021). This suggests that multiple methods of measuring aggregate stability are suitable for capturing soil structure changes related to reduced physical disturbance. However, the magnitudes of response to tillage for WSA_{CASH} and WSA_{ARS} were dependent on inherent soil properties and climate interactions. This indicates that reducing tillage will not uniformly increase measures of WSA_{CASH} and WSA_{ARS} across climates and soil textures. Although magnitudes of response to tillage differed for WSA_{CASH} and WSA_{ARS}, all four indicators' response to reduced tillage were positively correlated with changes in soil organic carbon and potential carbon mineralization. Elucidating the expected magnitude of change in aggregate stability indicators due to changes in management practices for a given location will provide stakeholders the context as to what increases in indicator values are realistically achievable following adoption of soil health management practices.

4.3. Indicator sensitivity and selection

All four indicators were moderately to highly correlated with each other. Additionally, while treatment coefficients of variation were not uniform across indicators, greater variation did not appear to impede response to management practices. In fact, WSA_{ARS}, which had the smallest within treatment coefficient of variation, was only significantly greater in two of the six soil health management practices analyzed, while the other indicators were significantly greater in three management practices. There was no consistency as to each of the indicator's three management practices, suggesting no indicator was the most sensitive to all management practices. Furthermore, indicators that were not significantly greater due to residue retention, organic nutrient amendments, or cover crop usage generally trended towards positive responses. These results suggest that sensitivity to management is dependent on the indicator, but positive responses to reduced tillage, cover crops, organic amendments, and residue retention can be expected across most of the aggregate stability indicators in this study.

To compare aggregate stability indicators across space, indicator sensitivity to inherent properties and climate must be considered. All aggregate stability indicators were sensitive to either climatic factors, inherent soil properties, or both to a certain degree, with $STAB_{10}$ being the most sensitive. This indicates that certain climates and soil types are likely to contain greater fractions of stable aggregates, regardless of management strategy. These results align with prior work, which identified greater concentrations of water stable aggregates in soils derived from wetter, cooler climates (Büchi et al., 2022; Cerdà, 2000). Furthermore, the methodological nature of $STAB_{10}$ and WSA_{CASH} revealed the positive influence of sand on stable aggregates. Additionally, the differing magnitudes of responses to tillage, based on climate and inherent soil properties for WSA_{ARS} and WSA_{CASH} further signify the need to incorporate inherent properties, into aggregate stability indicator assessments. Previous soil health assessments have included broadscale inherent soil properties and climatic effects to produce soil health scores, which in theory, are comparable across regions (Andrews et al., 2004; Moebius-Clune et al., 2016). However, more recent approaches for analyzing soil health have used finer spatial scales, where soils with a given set of inherent properties and climate are directly compared against one another (Nunes et al., 2021). Given the dependence of indicators on inherent soil properties and climate in this study, similar considerations should be made prior to comparison of aggregate stability measurements.

Although many aggregate stability methods have been developed by the scientific community, the tests must also be available at commercial labs for a reasonable price to be useful to producers and other stakeholders. Currently, to our knowledge, MWD is not available at any commercial laboratories because of the time-consuming nature of the method. Similarly, WSA_{CASH} is only available through the Cornell Soil Health Laboratory and Oregon State Soil Health Laboratory for a price of twenty dollars per sample. Wet sieve aggregate stability tests like WSA_{ARS} are available at several private laboratories and range in cost from fifteen to fifty dollars (personal communications). While $STAB_{10}$ isn't currently available commercially, the method is the least time consuming of those tested in this study and can be performed simply. Preliminary cost estimates from private laboratories for $STAB_{10}$ range from five to ten dollars per sample (personal communications). Providing a cost-effective aggregate stability indicator, such as $STAB_{10}$, will likely increase the number of stakeholders who are able to test the quality of their soils, which in turn, facilitates quantitative soil health monitoring and may reinforce management decisions that result in healthier soil.

5. Conclusions

Four measurements of aggregate stability were evaluated and compared based on their ability to assess soil quality. All four aggregate stability indicators analyzed in this study were sensitive, to a certain degree, to soil health management practices, inherent soil properties, and climate. While all four methods generally increased in treatments practicing reduced tillage, cover cropping, organic nutrient amendments, and residue retention, different subsets of indicators were significantly greater for each individual management practice evaluated in this study. This indicates that no one method was the most sensitive to all soil health management practices. Furthermore, all aggregate stability indicators were sensitive to climate and inherent soil properties at the continental scale, suggesting that measurements should be interpreted in this context. Overall, the similar responses to management practices suggest that all four methods analyzed in this study are suitable as measures of soil aggregate stability. Although the methods were correlated with each other ($0.45 \leq r \leq 0.69$), the associated variability suggests the methods are not interoperable. Therefore, it is important to consistently use the same method when monitoring changes in soil health over time. Secondary considerations, driven by project-specific constraints (e.g., budgets, method availability, within-treatment variability, increased sensitivity to a specific management practice) will determine the most appropriate method for a given investigation.

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.

Data availability

Data will be made available on request.

Acknowledgements

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Author contributions

E. Rieke collected soil samples, collected management data, analyzed data, and drafted and edited the manuscript. D. Bagnall analyzed data and drafted and edited the manuscript. C. Morgan supervised the project, contributed to analyses, and edited the manuscript. K. Flynn performed 10-min change in slaking via image analyses. J. Howe oversaw 10-min change in slaking via image analyses, aided in sampling, provided five years of comprehensive management data, and performed quality assurance and control on soil health data and standardized management information. Authors G. Bean through P.W. Tracy collected the samples, coordinated soil sampling and management data collection, and assistant in some analyses. Authors E. Aberle through D. Wright were partnering scientists on the North American Project to Evaluate Soil Health Measurements. Partnering scientists maintained the long-term research sites, provided assistance in sampling the sites, provided five years of comprehensive management data, and performing quality assurance and control on soil health data and standardized management information for each location. C.W. Honeycutt designed the study and acquired funding.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2022.116156.

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