Soil & Tillage Research 111 (2011) 99–104

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

A whole soil stability index (WSSI) for evaluating soil aggregation

K.A. Nichols [a,*], M. Toro [b]

[a] USDA-ARS Northern Great Plains Research Laboratory, P.O. Box 459, 1701 10th Ave SW, Mandan, ND 58554, United States
[b] Laboratorio de Estudios Ambientales, Instituto de Zoología Tropical, Facultad de Ciencias, Universidad Central de Venezuela, Caracas 1041-A, Apartado 47.058, Venezuela

ARTICLE INFO

Article history:
Received 19 May 2009
Received in revised form 24 August 2010
Accepted 26 August 2010

Keywords:
Whole soil stability index
Water-stable aggregation
Dry aggregate size distribution
Normalized stability index

ABSTRACT

Soil aggregate stability is a frequently used indicator of soil quality, but there is no standard methodology for assessing this indicator. Current methods generally measure only a portion of the soil or use either dry-sieved or wet-sieved aggregates. Our objective was to develop a whole soil stability index (WSSI) by combining data from dry aggregate size distribution and water-stable aggregation along with a 'quality' constant for each aggregate size class. The quality constant was based on the impact of aggregate size on soil quality indicators. Soil quality indicators can be loosely defined as those soil properties and processes that have the greatest sensitivity to changes in soil function. The WSSI was hypothesized to have a better relationship to the impacts of aboveground management than other soil aggregation indices such as a mean weight diameter (MWD), geometric mean diameter (GMD), and the normalized stability index (NSI). Soil samples used in this study were collected from sites established on the same or similar soil types at the Northern Great Plains Research Laboratory in Mandan, ND. By utilizing dry aggregate size distribution, water-stable aggregation, and the quality constant, the WSSI detected differences in soil quality due to management (such as amount of disturbance, plant cover, and crop rotation) with the highest values occurring for the undisturbed, native range and the lowest values for conventional tillage, fallow treatments. The WSSI had the best relationship with management and is recommended as a standard measurement for soil aggregation.

Published by Elsevier B.V.

1. Introduction

Soil organic matter levels, soil biological activity, and soil functions (such as water infiltration, water holding-capacity, aeration, and nutrient availability) are related to soil aggregation (Pirmoradian et al., 2005; Six et al., 2004). A variety of time-consuming and complex methods exist for measuring soil aggregation, however these methods frequently measure only a portion of the whole soil (i.e. one or more aggregate size class) (Six et al., 2004) and seldom separate dry aggregate size distribution (i.e. aggregate formation) from water-stable aggregation (WSA) (i.e. aggregate stabilization) (Allison, 1968; van Steenbergen et al., 1991), and are not quantitatively related to soil quality. Measurements of soil quality are dependent upon which chemical, biological or physical indicators are measured and how those indicators are interpreted (Andrews et al., 2004; Carter, 2002; Karlen et al., 2003). This makes soil quality assessment vulnerable to subjective interpretation based on the perspective and the level of scientific knowledge of the user.

Aggregate size distribution – the amounts of large, medium, and small macroaggregates (>250 μm) and microaggregates (<250 μm) – influence pore size and continuity (Six et al., 2004). Macroaggregates typically have more organic matter and higher nutrient levels, are less susceptible to erosion, and create larger pores for better water infiltration and aeration than microaggregates (Elliott, 1986; Niewczas and Witkowska-Walczak, 2003; Six et al., 2004). Therefore, a soil with more stable macroaggregates will be of a higher quality than a soil with more stable microaggregate. However, if a soil consists solely of large macroaggregates, the pore size between these aggregates will be large with little water and nutrient retention. If all the aggregates in the soil are 100% stable, the soil surface will be sealed reducing water infiltration and soil function. This would be similar to soils which have high soil water repellency or hydrophobicity due to a relative saturation of hydrophobic substances, such as organic matter or microbial by-products (Buczko and Bens, 2006). A combination of aggregate sizes and stabilities are needed for 'ideal' soil function and quality. In this study, a weighted factor based on the interactions between soil aggregation and soil function which may better address management impacts was included in the equations for the whole soil stability index (WSSI). The use of a

Abbreviations: IR, idle rangeland; MT, minimum till; NSI, normalized stability index; NT, no till; R, rye; S, safflower; SQM, soil quality management experiment; SW, spring wheat; WSA, water-stable aggregation; WSSI, whole soil stability index.

* Corresponding author. Tel.: +1 701 667 3008; fax: +1 701 667 3054.
E-mail addresses: Kristine.Nichols@ars.usda.gov (K.A. Nichols), marcia.toro@ciens.ucv.ve (M. Toro).

0167-1987/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.still.2010.08.014

quality factor in the WSSI is similar to Niewczas and Witkowska-Walczak (2005) using a quality factor in their aggregation stability index or the Soil Management Assessment Framework (SMAF) assessing soil quality using a more-is-better curve for soil aggregation (Andrews et al., 2004; Karlen et al., 2003).

Macroaggregates are formed and stabilized by biological factors, such as roots and fungal hyphae and by-products of microbial synthesis and decay (Karlen et al., 1992; Lado et al., 2004; Tisdall and Oades, 1982). Microaggregates are more often formed and stabilized by chemical factors, such as clay mineralogy (Six et al., 2004; Tisdall and Oades, 1982). Therefore, aboveground management including tillage practices, crop rotation/sequencing, fertilizer application, pesticide application, and water management impact macroaggregation more than microaggregation (Elliott, 1986; Kemper and Rosenau, 1986; Pirmoradian et al., 2005; Six et al., 2004; van Steenbergen et al., 1991)

A number of the indices have been proposed for assessing soil stability including mean weight diameter (MWD), geometric mean diameter (GMD), water-stable aggregation (WSA) (Kemper and Rosenau, 1986), aggregate stability index (ASI) (Niewczas and Witkowska-Walczak, 2003), and normalized stability index (NSI) (Six et al., 2004), but these indices either lack a clear differentiation between stable and unstable macroaggregates or apply only to a specific set of aggregate sizes and not the whole (Marquez et al., 2004). These indices also may be biased by procedural factors which may contribute to the artificial decomposition of large aggregates into a smaller aggregates by abrasion against the screens or collision of large-sized particles against smaller-sized particles. In addition, soil aggregate stability indices rarely express numerically the impacts of mechanical, environmental, or biological factors.

The WSSI methodology outlined here uses dry aggregate size distribution and water-stable aggregation (WSA) as variables along with constants which are quantitative surrogates for the qualitative benefits conveyed by different aggregate sizes. Dry aggregate size distribution measures the amount of aggregates formed but does not address the stability of these aggregates whereas WSA is used to determine the stability of these aggregates. Other methodology attempts to separate aggregate formation from aggregate stabilization by differentiating between unstable and stable aggregates using the capillary rewetting and slaking procedures (Gale et al., 2000; Six et al., 2004), but this underestimates the amount of aggregates formed and identifies stable aggregates only as those able to survive slaking.

In this study, treatments with different tillage histories – never-tilled (ZT), no till (NT), minimum tillage (MT), and conventional tillage (CT) – and cropping intensities were applied to plots on the same or similar soil types in the same climatic region. These treatments were ranked according to level of disturbance and amount and type of plant cover with the CT fallow treatment at the low end and ZT, range at the high end (Table 2). A whole soil stability index (WSSI) was calculated for each treatment and related to the treatment rank, mean weight diameter (MWD), geometric mean diameter (GMD) (Kemper and Rosenau, 1986), and the normalized stability index (NSI) (Six et al., 2000).

2. Methods

2.1. Soil samples

Soil samples were collected from both cropland and rangeland sites located at the Northern Great Plains Research Laboratory in Mandan, ND. These sites were established on gently rolling uplands (0–3% slope) on the Missouri Plateau in north central USA. All of the treatments were located at sites with predominantly Temvik-Wilton silt loam soils, except for the conventionally tilled (CT), chemical fallow treatment which was on a Parshall sandy loam. Both soils are fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls. Average annual precipitation is 409 mm and temperature is 4 °C with a range from 21 °C in summer to −11 °C in winter.

The soil disturbance level (i.e. tillage history) and the length of time and type of plant cover were used to rank each treatment prior to measuring the stability indices with the CT treatment on one end and the zero tillage (ZT) treatments on the other (Table 2). The first treatment was the CT, chemical fallow (Fallow) treatment which was the buffer strip around grass breeding plots and had been maintained for more than 15 years. The second was a chemical fallow-spring wheat (*Triticum aestivum* L.) (F-SW) rotation experiment established in 1984 under CT until it was converted to no till (NT) in 1999. The next 10 treatments were part of a long-term soil quality management (SQM) experiment established in 1993 (Liebig et al., 2004). At the SQM site, samples were collected from two tillage treatments – minimum tillage (MT) and no tillage (NT) – with three crop rotation sequences in each tillage treatment: 1. continuous spring wheat (*T. aestivum* L.) with the residue removed (CSW^-); 2. continuous spring wheat with the residue present (CSW^+), and 3. spring wheat, safflower (*Carthamus tinctorius* L.), and rye (*Secale cereale*). The final two treatments – a moderately grazed pasture (MGP) established in 1916 and an idle rangeland (IR) that had not been grazed or hayed for at least 20 years – had no tillage. Soil samples were collected at 0 to 10 cm using a hand trowel with one to ten samples composited per site as point-in-time measurements used to compare soil aggregation indices and not treatments. Samples were collected in Fall, 2005 following the first hard freeze at the SQM site and in Spring, 2006 after spring thaw at the other sites. (Preliminary data for samples collected from the SQM site in Spring, 2006 for a larger study showed no significant differences between samples collected in Fall, 2005 and Spring, 2006.) Large clods were gently broken up along natural fracture lines and samples were air-dried at 27 °C.

2.2. Stability indices

Whole soil stability index (WSSI). Aggregate distribution and water-stable aggregation (WSA) were measured on dry-sieved aggregates in four aggregate size classes (9.5–2, 2–1, 1–0.25, and 0.25–0.053 mm). Dry sieving consisted of placing the soil atop a screen with the size equal to the size of the largest aggregates in the size class, tapping the sides at least 50 times with the palm of the hand to pass the soil through the screen, collecting the soil passing through the screen on a piece of kraft paper, and pouring it onto a screen equal to the smallest aggregates in the size class followed by tapping. Each aggregate size class was collected individually from largest to smallest. The weight of aggregates in each size class was measured and used to calculate the proportion of aggregates in each size class relative to the whole soil (Eq. (1)). Soil on top of the 9.5 mm screen and below the 0.053 mm screen was collected and weighed as part of the summed total weight (W_T).

The proportion of dry-sieved aggregates in each size class was:

$$P_{ai} = \frac{[W_A - [(W_c/W_o) \times W_A]]}{W_T} \quad (1)$$

where P_{ai} = proportion of dry-sieved aggregates for each size class i; W_A = weight of total material in each size class i; W_c = weight of coarse material measured during wet sieving for size i (see Eq. (2)); W_o = weight of aggregates placed on the sieve prior to wet sieving size i (see Eq. (2)); W_T = summed total weights of all the aggregate size classes plus the soil from above the 9.5 mm screen and below the 0.053 mm screen.

Water-stable aggregation (WSA) was measured on four subsamples from each aggregate size class according to a modified Kemper and Rosenau (1986) method. Briefly, aggregates (4 g for the 9.5–2 and 2–1 mm aggregates, 2 g for the 1–0.25 mm aggregates, and 1 g for the 0.25–0.053 mm aggregates) were placed onto screens 1/4 of the smallest size and capillary-rewetted for 10 min. Stable aggregates were separated via mechanical wet sieving for 5 min using an apparatus described by Kemper and Rosenau (1986). Material collected on the sieve was washed gently into weigh boats, dried at 70 °C and weighed. The coarse material (sand, roots, and particulate organic matter) was removed by dispersing the aggregates in 0.5% sodium hexametaphosphate, shaking periodically over a 5 min period, and using forced water and rubber policemen to push the disrupted aggregates through a screen matching the smallest aggregates in the size class. The material remaining on the screen was collected, dried at 70 °C, weighed and subtracted from the weight of aggregates collected after wet sieving. The formula for calculating the WSA for each size class was:

$$\mathrm{WSA}_i = [(W_\mathrm{a} - W_\mathrm{c}) \div W_\mathrm{o}] \times 100 \quad (2)$$

where WSA_i = water-stable aggregation for each size class i; W_a = weight of material on the sieve after wet sieving size i; W_c = weight of coarse material in size i; W_o = weight of aggregates placed on the sieve prior to wet sieving size i.

The dry aggregate size distribution and WSA calculated above were used in the formula for the whole soil stability index (WSSI).

$$\mathrm{WSSI} = \left[\sum_{i}^{n}[(I) \times (P_{ai}) \times ((\mathrm{WSA}_i) \div 100)]\right] \div n \quad (3)$$

where WSSI = whole soil stability index; n = the number of the aggregate size classes; $i = n$ and decreases by an increment of 1 from the largest to the smallest aggregate sizes class; P_{ai} = proportion of aggregate weight for each size class i from Eq. (1); WSA_i = water-stable aggregation for each size class i from Eq. (2). Table 1 gives two examples of how the WSSI was calculated.

The maximum and minimum WSSI were theoretical values calculated using methodology similar to that described by Niewczas and Witkowska-Walczak (2005) where the maximum WSSI assumes all of the aggregates in a particular size class were 100% stable and the minimum WSSI assumes all the aggregate size classes had a stability of zero accept for the smallest aggregate size class which was 100% stable. The experimental WSSI values were then divided by the maximum WSSI values and multiplied by 100 to calculate how close the experimental WSSI values were to the maximum WSSI values.

Mean weight diameter and geometric mean diameter: Data used in the calculation of the WSSI was also used to calculate the mean weight diameter (MWD) and geometric mean diameter (GMD) according to the equations in Kemper and Rosenau (1986). These indices were compared to the WSSI values.

Normalized stability index: A normalized stability index (NSI) was measured on selected soil samples (10–25 g) from the SQM treatments and the ZT, IR treatment according to the procedures described by Six et al. (2000). Briefly, 12 duplicate samples from each treatment were separated into three groups of four. One group was rewetted at 4 °C overnight prior to wet sieving (capillary). Another group was wet-sieved without rewetting (slaked), and the final group was processed for a maximum disruption to measure the coarse material. Maximum disruption used forced water to destroy aggregates and wash them through stacked sieves. The capillary-rewetted and slaked samples were wet-sieved for 2 min through three screens (2, 0.25, and 0.053 mm) individually by transferring the material that went through the screen onto the next smaller screen. The material (i.e. water-stable aggregates) on screens in both the capillary-rewetted and slaked treatments was collected, dried at 70 °C, weighed, and corrected for the coarse material (i.e. sand and organic matter). The NSI was calculated using the equations provided by Six et al. (2000).

2.3. Statistical analysis

Treatment means were calculated for the WSSI, MWD, GMD, and NSI measurements. Regression analysis was performed to test the relationships between the treatment rank, WSSI, MWD, GMD, and NSI using SAS software, ver. 9.1 after meeting the normality

Table 1
Examples of the data collected and calculations for measuring dry aggregate distribution, water-stable aggregation (WSA) and a whole soil stability index (WSSI).

	Example 1	Example 2
Total weight of soil sample	200 g	150 g
Weight of 9.5–2 mm aggregates	95 g	18 g
Weight of 2–1 mm aggregates	35 g	13 g
Weight of 1–0.25 mm aggregates	50 g	52 g
Weight of 0.25–0.053 mm aggregates	40 g	69 g
Weight of original sample on 0.5 mm screen (9.5–2 mm aggregates)	4 g	4 g
Weight of original sample on 0.25 mm screen (2–1 mm aggregates)	4 g	4 g
Weight of original sample on 0.063 mm screen (1–0.25 mm aggregates)	2 g	2 g
Weight of original sample on 0.015 mm screen (0.25–0.053 mm aggregates)	1 g	1 g
Weight of material on 0.5 mm screen after wet sieving	2.6 g	0.5 g
Weight of material on 0.25 mm screen after wet sieving	3.7 g	1.9 g
Weight of material on 0.063 mm screen after wet sieving	1.8 g	1.8 g
Weight of material on 0.015 mm screen after wet sieving	0.9 g	1.0 g
Weight of coarse 9.5–2 mm coarse material	0.7 g	0.1 g
Weight of coarse 2–1 mm coarse material	0.2 g	1.0 g
Weight of coarse 1–0.25 mm coarse material	0.3 g	0.3 g
Weight of coarse 0.25–0.053 mm coarse material	0.6 g	0.7 g
WSA for 9.5–2 mm aggregates	48%	10%
WSA for 2–1 mm aggregates	88%	23%
WSA for 1–0.25 mm aggregates	75%	75%
WSA for 0.25–0.053 mm aggregates	30%	30%
Proportion of aggregate weight for 9.5–2 mm aggregates	0.39	0.12
Proportion of aggregate weight for 2–1 mm aggregates	0.17	0.07
Proportion of aggregate weight for 1–0.25 mm aggregates	0.21	0.29
Proportion of aggregate weight for 0.25–0.053 mm aggregates	0.08	0.14
WSSI	0.52	0.29

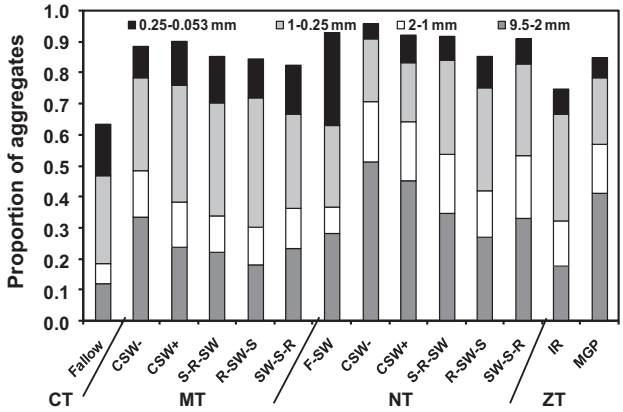

Fig. 1. The proportion of total soil sample by weight comprised of aggregates in each of the four aggregate size classes for the conventionally tilled (CT) chemical fallow (Fallow); minimum (MT) and no (NT) till continuous spring wheat with residue removed (CSW^-), continuous spring wheat without residue removed (CSW^+), and spring wheat–safflower–rye (SW–S–R) crop sequences (SW–S–R, S–R–SW, R–SW–S); the NT fallow-spring wheat (NT, F-SW); and zero till (ZT) idle rangeland (IR) and moderately grazed pasture (MGP) treatments.

assumption (SAS Institute, 2005). Comparisons between treatments are used to illustrate how the data related to management more than illustrating differences between treatments which would require a large study with more replicate samples.

3. Results

Most of the soil (>63%) was present in one of the four aggregate size classes collected with the lowest amount in the fallow sample (Fig. 1). Of the four sizes collected, more than 80% of the mass was in the macroaggregate size classes except for the Fallow and NT, F-SW treatments which had 74% and 68%, respectively. Generally, the NT and ZT, MGP treatments had the highest proportions of the large macroaggregates (9.5–2 mm), while the MT and CT treatments had more in the small macroaggregate size class (1–0.25 mm).

The Fallow and NT, F-SW treatments had the lowest total percentage of WSA while the two ZT treatments had WSA percentages >74% in all three of the macroaggregate size classes (Fig. 2). For the SQM treatments, the average WSA values were 27%, 33%, 79%, and 55% in the 9.5–2, 2–1, 1–0.025, and 0.25–0.053 size classes, respectively.

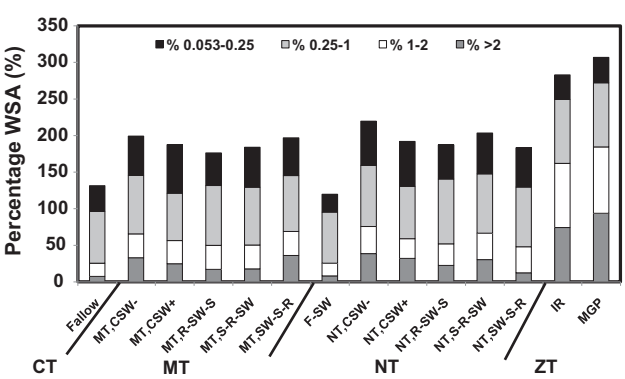

Fig. 2. The percentage of water-stable aggregates (WSA) for the four aggregate size classes for the conventionally tilled (CT) chemical fallow (Fallow); minimum (MT) and no (NT) till continuous spring wheat with residue removed (CSW^-), continuous spring wheat without residue removed (CSW^+), and spring wheat–safflower–rye (SW–S–R) crop sequences (SW–S–R, S–R–SW, R–SW–S); the NT fallow-spring wheat (NT, F-SW); and zero till (ZT) idle rangeland (IR) and moderately grazed pasture (MGP) treatments.

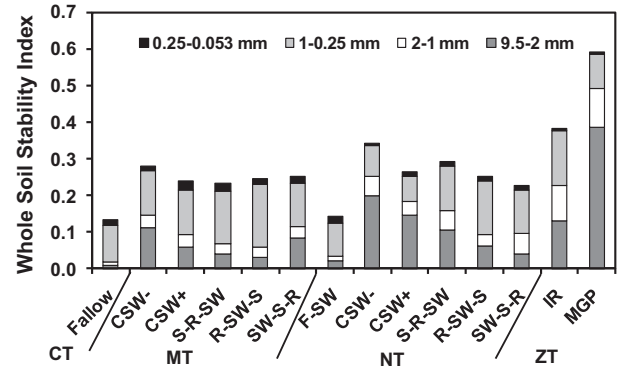

Fig. 3. The whole soil stability index (WSSI) for each of the four aggregate size classes for the conventionally tilled (CT) chemical fallow (Fallow); minimum (MT) and no (NT) till continuous spring wheat with residue removed (CSW^-), continuous spring wheat without residue removed (CSW^+), and spring wheat–safflower–rye (SW–S–R) crop sequences (SW–S–R, S–R–SW, R–SW–S); the NT fallow-spring wheat (NT, F-SW); and zero till (ZT) idle rangeland (IR) and moderately grazed pasture (MGP) treatments.

The MGP treatment had the highest WSSI at 0.59 followed by the IR treatment while the NT, F-SW and Fallow treatments had the lowest WSSI values (Fig. 3). The macroaggregate size classes had the highest stability indices compared to the microaggregate size class. Although 30% of the whole soil weight was in the microaggregate size class for the NT, F-SW treatment (Fig. 1), the low WSA value (Fig. 2) combined with the lowest soil quality factor for this size resulted in a low stability index value for this size class and for the treatment overall. The ZT WSSI values were 80% and 91% of their maximum values for the IR and MGP treatments, respectively (Table 2). The highest WSSI max values were for the NT, CSW^- and CSW^+ treatments, but the test WSSI values were less than 45% of this maximum (Table 2). The highest WSSI min value was for the NT, F-SW and the lowest value was for the NT, CSW^-.

Regression analysis of the WSSI, MWD, GMD, and NSI values to the treatment rank (R^2 = 0.4972, 0.1074, 0.1419, and 0.1595, respectively; Fig. 4) showed the strongest relationship between with the WSSI.

Table 2
The treatment rank based on level of disturbance, rotation, and plant cover; whole soil stability index (WSSI); the WSSI maximum (max) based on 100% water-stable aggregation (WSA) levels for the aggregates in each aggregate size class; the WSSI minimum (min) based on 0% WSA for all the macroaggregate size classes (>0.25 mm) and 100% WSA for the microaggregate size class (<0.25 mm); the WSSI % calculated by comparing the WSSI and WSSI max values; and the min/max range or difference between the WSSI max and WSSI min values for the zero till (ZT) idle rangeland (IR) and moderately grazed pasture (MGP); minimum (MT) and no (NT) till continuous spring wheat with residue removed (CSW^-), continuous spring wheat without residue removed (CSW^+), and spring wheat–safflower–rye (SW–S–R) crop sequences (SW–S–R, S–R–SW, R–SW–S); the NT fallow-spring wheat (NT, F-SW); and the conventionally tilled (CT) chemical fallow (Fallow) treatments.

ID	Treatment rank	WSSI	WSSI max	WSSI min	WSSI%	min max range
CT, Fallow	1	0.133	0.351	0.041	38.0	0.311
NT, F-SW	2	0.143	0.552	0.075	26.0	0.477
MT, CSW^-	3	0.281	0.623	0.025	45.1	0.598
MT, CSW^+	4	0.239	0.571	0.036	41.9	0.535
MT, R–SW–S	5	0.246	0.512	0.032	48.0	0.480
MT, S–R–SW	5	0.232	0.528	0.038	44.0	0.490
MT, SW–S–R	5	0.253	0.522	0.039	48.5	0.482
NT, CSW^-	6	0.344	0.772	0.012	44.5	0.760
NT, CSW^+	7	0.265	0.712	0.022	37.4	0.690
NT, R–SW–S	8	0.252	0.574	0.025	44.0	0.548
NT, S–R–SW	8	0.292	0.661	0.019	44.1	0.642
NT, SW–S–R	8	0.226	0.649	0.020	34.9	0.629
ZT, IR	9	0.384	0.478	0.021	80.3	0.457
ZT, MGP	10	0.593	0.654	0.016	90.7	0.638

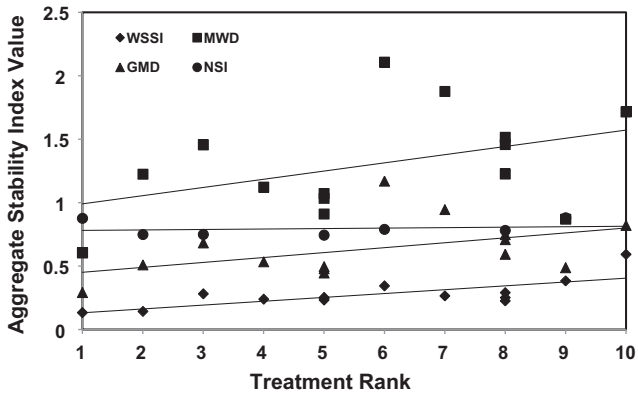

Fig. 4. Relationships between the system rank based on management, whole soil stability index (WSSI), the mean weight diameter (MWD), geometric mean diameter (GMD), and the normalized stability index (NSI).

4. Discussion

A well-aggregated soil has good structure and tilth, but understanding the processes involved in aggregate formation and stabilization and quantifying aggregation is difficult (Allison, 1968; Marquez et al., 2004; Niewczas and Witkowska-Walczak, 2003). Aggregate formation involves wetting and drying cycles; freezing and thawing; the orientation, size and properties of clay minerals; transient and temporary organic binding agents; root and fungal growth; chemical and electrical forces; etc. (Allison, 1968; Six et al., 2004). Aggregate stabilization involves persistent organic substances and their interactions with clay minerals where the forces inside the aggregate created by these interactions are greater than the forces outside the aggregate (Allison, 1968; Kemper and Rosenau, 1986; Six et al., 2004). An index for measuring aggregation needs to account for the differences between aggregate formation, stability, and sand content as well as the relationship between aggregation and soil quality.

In this study, the aggregate distribution values were much higher for the 9.5–2, 2–1, and 1–0.25 mm size classes, or macroaggregates, in the ZT and NT systems, particularly the 9.5–2 mm aggregates in the ZT, MGP and NT, CSW^- and CSW^+ treatments (Fig. 1). This indicates less disruption by tillage allows more extensive hyphal growth and macroaggregate formation. The ZT treatments (IR and MGP) also had the highest WSA values for the macroaggregate size classes (Fig. 2). Since these treatments have the longest duration of living plant cover, the carbon compounds coming directly or indirectly from the plant through the soil biological food web probably have the greatest stabilizing forces. At the SQM site, the treatments with no tillage had the WSSI values higher than the same treatments under MT (Fig. 3). The CSW^- treatments had higher WSA and WSSI values than expected given the lack of diversity and residue cover in this treatment, but it was noted that following wheat harvest and residue removal, there would be a flush of plant growth (M.A. Liebig, personal communication). The SQM site had a spring herbicide application only (Liebig et al., 2004) which means the plant growth following harvest and residue removal might have like an unexpected cover crop and stimulated aggregate formation and stabilization. The importance of length of time with a living plant growing on WSA and WSSI was also exhibited in the NT, F-SW treatment which had the lowest values of all the cropped treatments.

The WSSI methodology introduced here has many similarities to other soil aggregation indices (Niewczas and Witkowska-Walczak, 2003; Kemper and Rosenau, 1986; Six et al., 2000; van Steenbergen et al., 1991). However, the WSSI has the following advantages over other aggregation indices: 1. it examines aggregate formation and aggregate stability separately; 2. the methodology/equations are flexible as to the pre-treatments, sieving methodology and number and size of aggregate sizes classes; 3. it uses single sieves rather than stacked sieves; and 4. it provides a quantitative constant for integrating qualitative soil quality aspects. By separating aggregate formation from aggregate stabilization, this method accounts for the impacts of these processes on soil quality and allows for the forces which contribute to these processes (such as biological factors, clay mineralogy, and polyvalent cation concentrations) to be analyzed separately. The flexibility allows this method to be applied to a variety of experimental objectives and conditions and to be manipulated to handle widely differing soils. Kemper and Rosenau (1986) stated different pre-treatment conditions or different wet sieving times or strokes may be necessary to handle samples from sodic or high humidity soils where stability may be close to 100% or for soils with concretions formed by $CaCO_3$, iron oxides, organic matter, etc. Using single sieves reduces the frequency of sieve clogging, prevents aggregates or coarse material from being retained on the wrong sieve because of sieve overloading, prevents the destruction of small aggregates by the sheering forces of large aggregates present on the sieve simultaneously, reduces the abrasion of large aggregates against the screen while trying to collect the smaller aggregates on the screens below, and prevents coarse material or microaggregates within larger aggregates from being collected on the smaller screens during wet sieving biasing the weight of the smaller aggregate size classes. The disadvantages of using single sieves are the amount of time needed to conduct all the sieving and the difficulty in collecting and analyzing microaggregates present within macroaggregates released during wet sieving.

As discussed by Karlen et al. (2003), Carter (2002), and others, the soil quality concept is one which describes an objective condition of the soil, but it is also subjective and is a matter of personal and social interpretation. The addition of the constant in the equation accounts for the subjective aspects of soil quality by providing a factor that is developed from relationships between soil aggregation and soil functions, such as water infiltration, water retention, erosion resistance, and nutrient cycling. This is similar to the scoring system used in SMAF which is based upon current scientific knowledge, literature review, and consensus of collaborating researchers to develop the shapes of the curves for each soil quality indicator (Andrews et al., 2004; Karlen et al., 2003). The aggregate stability indicator in SMAF is given a more better shape which is reflected in the WSSI as a larger constant for larger aggregate sizes.

The WSSI, MWD, GMD, and NSI were compared to the rank values for each treatment to determine which index was best suited for assessing differences in treatments. Although the MWD and GMD were calculated on the same samples used for the WSSI, these values could only be calculated on the dry-sieved aggregates which resulted in a low relationship with treatment rank (Fig. 4). Since the NSI was calculated on different subsamples isolated from the soil sample and, according to Six et al. (2000), this index is supposed to detect differences in management at the same site, the low relationship (R^2 = 0.1595) between this index and treatment rank (Fig. 4) was unexpected. These disadvantages when using NSI are: 1. using different subsamples for each of the three wet sieving procedures—capillary rewetting, slaking, or maximum disruption for collection of the coarse material, 2. subtracting the slaked values from the capillary-rewetted values and ending up with zero values, and 3. having more zero values for the macroaggregates than microaggregates due to the greater weight in each macroaggregate which favors microaggregates over macroaggregates (Marquez et al., 2004; Six et al., 2000). In this study, the NSI values overall were higher than the WSSI values due to the calculations used, but samples with the higher amounts of small

macroaggregates and microaggregates (Fig. 1) in the WSSI methodology also had high NSI values (Fig. 4). The weak relationships between the treatment ranking and all the indices may have resulted from the criteria used for ranking not being sufficient and the similarities between all the treatments at the SQM site.

Capillary rewetting was used as the pre-treatment over slaking because studies showed that this pre-treatment had the least variability (Beare and Bruces, 1993; Kemper and Rosenau, 1986) and only a small portion of aggregates on the soil surface (down to 1.2 mm) would be exposed to the impact of raindrops, similar to the slaking pre-treatment (Lado et al., 2004). Kemper and Rosenau (1986) also argue that since aggregate stability is measured under some arbitrary disintegrating force, the values are empirical and only have meaning when compared to values from other soils or treatments using the same methodology. Therefore, any stability index is only a point-in-time measurement and if comparisons are being made across treatments or soils, samples should be collected at the same time because comparisons across time would be limited by growing conditions – temperature, rainfall, and season (Six et al., 2004). van Steenbergen et al. (1991) argue that capillary rewetting does not account for differences in stable and unstable macroaggregates without slaking. However, since the methodology outlined here separates those two components, it is not a factor in this index.

Although measurements were made on a number of different treatments, this study was not designed to compare treatments but rather to determine if differences between treatments could be detected. The treatments with the highest and lowest potential to improve soil quality were also the treatments with the highest and lowest WSSI, respectively (Fig. 4). When the expected results were less clear for determining rank (as at the SQM site), the relationships aggregation indices and soil quality were more difficult to measure. To further examine the interactions between WSSI and soil quality, a larger study is being conducted comparing treatments, the WSSI, and other soil quality parameters, including the glomalin fraction. Although the WSSI method appears to be time-consuming and complex, it has the potential to examine soil aggregation in another way and to characterize organic carbon, nitrogen, or other nutrient distributions in a soil sample based on aggregate size association. The WSSI methodology may assist future research on the soil biological and/or soil organic matter characteristics associated with the process of soil aggregate formation and how these may differ with those involved in aggregate stability.

Disclaimer

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

Acknowledgments

The authors would like to acknowledge Crystal Jundt and Amy Kulackoski for their assistance with the laboratory analysis.

References

Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68, 1945–1962.

Allison, F.E., 1968. Soil aggregation—some facts and fallacies as seen by a microbiologist. Soil Sci. 106 (2), 136–143.

Beare, M.H., Bruces, R.R., 1993. A comparison of methods for measuring water-stable aggregates: implications for determining environmental effects on soil structure. Geoderma 56, 87–104.

Buczko, U., Bens, O., 2006. Assessing soil hydrophobicity and its variability through the soil profile using two different methods. Soil Sci. Soc. Am. J. 70, 718–727.

Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron. J. 94, 38–47.

Elliott, E.T., 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. Soil Sci. Soc. Am. J. 50, 627–633.

Gale, W.J., Cambardella, C.A., Bailey, T.B., 2000. Surface residue- and root-derived carbon in stable and aggregates. Soil Sci. Soc. Am. J. 64, 196–201.

Karlen, D.L., Eash, N.S., Unger, P.W., 1992. Soil and crop management effects on soil quality indicators. Am. J. Altern. Agric. 7, 48–55.

Karlen, D.L., Andrews, S.S., Weinhold, B.J., Doran, J.W., 2003. Soil quality: humankind's foundation for survival. J. Soil Water Conserv. 58 (4), 171–179.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis, Part I. 2nd ed. ASA Madison, WI, p. 425-442.

Lado, M., Paz, A., Ben-Hur, M., 2004. Organic matter and aggregate size interactions in infiltration, seal formation, and soil loss. Soil Sci. Soc. Am. J. 68, 935–942.

Liebig, M.A., Tanaka, D.L., Wienhold, B.J., 2004. Tillage and cropping effects on soil quality indicators in the Northern Great Plains. Soil Till. Res. 78, 131–141.

Marquez, C.O., Garcia, V.J., Cambardella, C., Schultz, R.C., Isenhart, T.M., 2004. Aggregate-size stability distribution and soil stability. Soil Sci. Soc. Am. J. 68, 725–735.

Niewczas, J., Witkowska-Walczak, B., 2005. The soil aggregates stability index (ASI) and its extreme values. Soil Till. Res. 80, 69–78.

Niewczas, J., Witkowska-Walczak, B., 2003. Index of soil aggregate stability as linear function value of transition matrix elements. Soil Till. Res. 70 (2), 121–130.

Pirmoradian, N., Sepaskhah, A.R., Hajabbasi, M.A., 2005. Application of fractal theory to quantify soil aggregate stability as influenced by tillage treatments. Biosyst. Eng. 90 (2), 227–234.

SAS Institute, Inc. 2005. SAS User's Guide: Statistics, Release 9.1. Cary, NC.

Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. 79, 7–31.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil structure and soil organic matter. II. A normalized stability index and the effect of mineralogy. Soil Sci. Soc. Am. J. 64 (3), 1042–1049.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

van Steenbergen, M., Cambardella, C., Elliott, E.T., Merckx, R., 1991. Two simple indices for distributions of soil compoenents among size classes. Agric. Ecosys. Environ. 34, 335–340.