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Aggregate-Size Stability Distribution and Soil Stability

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Keywords
size-stability, soil aggregates, slaking, riparian buffer

Disciplines
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ABSTRACT

A new theoretical and experimental framework that permits an accurate determination of aggregate-size stability distribution is presented. The size-stability distribution in addition to estimating aggregate-size distribution distinguishes between amounts of stable and unstable macroaggregates (>250 μm). The determination of aggregate-size stability distribution involves the assumptions that soil aggregates can be categorized in terms of their size and water stability (slaking resistance). Experimentally this procedure involves the slaked and capillary-wetted pretreatments; and a subsequent slaking treatment of aggregates >250 μm in size. We also propose the stable aggregates index (SAI) and the stable macroaggregates index (SMaI) for studying soil stability based on aggregate resistance to slaking. These indices account for the total weighted average of stable aggregates and the total weighted average of stable macroaggregates, respectively. Both the SAI and the SMaI indices were shown to be sensitive to the effects of vegetation on soil stability under different riparian buffer communities. The SAI and the SMaI indices were higher in surface soils under cool-season grass than any of the other treatments. These soils samples are well aggregated with SAI = 74% and SMaI = 56% followed by SAI = 55% and SMaI = 37% under existing riparian forest, SAI = 40% and SMaI = 21% under 7-yr switchgrass and SAI = 36% and SMaI = 18% under cropped system.

Soil aggregate stability is the result of complex interactions among biological, chemical, and physical processes in the soil (Tisdall and Oades, 1982). Factors affecting aggregate stability can be grouped as abiotic (clay minerals, sesquioxides, exchangeable cations), biotic (soil organic matter, activities of plant roots, soil fauna, and microorganisms), and environmental (soil temperature and moisture) (Chen et al., 1998). The concept of aggregate stability depends on both the forces that bind particles together and the nature and magnitude of the disruptive stress (Beare and Bruce, 1993).

Several methods have been proposed to determine soil aggregate-size distribution and stability (Kemper and Rosenau, 1986). The suitability of these methods depends on the purpose of the study. The most widely used approaches are based on the wet-sieving method (Kemper, 1966; Kemper and Rosenau, 1986). In this method, cyclically submerging and sieving soil in water emulates the natural stresses involved in the entry of water into soil aggregates. The moisture content of the soil aggregates before wet sieving controls the severity of the disruption (Kemper and Rosenau, 1986). Several studies have used capillary-wetted and slaked pretreatments (Elliott, 1986; Cambardella and Elliott, 1993a; Six et al., 1998) as a means to study soil aggregates. The capillary-wetted pretreatment involves slowly wetting the soil aggregates before wet sieving. This pretreatment produces minimal disruption, because misted aggregates do not buildup air pressure in the pores and the air escapes with minimal aggregate disruption. In contrast, the slaked pretreatment causes considerable disruption. When air-dry soil is submerged in water; the air that is trapped inside the soil pores is rapidly displaced with water. Weak aggregates are disrupted as a consequence of the sudden release of this large buildup of internal air pressure (Cambardella and Elliott, 1993a; Gale et al., 2000).

The combined use of the capillary-wetted and the slaked pretreatments has been used for contrasting differences in aggregate-size distributions for soils with different management histories and also for understanding the factors that influence aggregate stability (Elliott, 1986; Cambardella and Elliott, 1993a; Six et al., 1998). More recently, Gale et al. (2000) used the comparison of slaked versus capillary-wetted pretreatments as a means to differentiate stable macroaggregates from unstable macroaggregates based on their resistance to slaking. Although the conceptualization of Gale's idea represents an important contribution, more work is needed to clearly separate the stable macroaggregates from the unstable macroaggregates and accurately specify aggregate-size stability distributions. The aggregate-size stability distribution is the quantity of stable and unstable soil aggregates categorized by their size and stability to disruption.

Existing approaches for studying soil aggregates do not fully distinguish between stable and unstable aggregates based on their resistance to slaking. In turn, this causes significant errors in assessing soil stability by the wet-sieve method and the dynamics of soil aggregates and the C associated with aggregates. The disruption of unstable macroaggregates during the slaking treatment produces smaller constituent aggregates that are accounted for in smaller aggregate-size fractions biasing the aggregate-size distribution. In contrast, the capillary-wetted pretreatment does not account for differences in stable and unstable macroaggregates because of the lack of violent disruption.

We hypothesize that using a subsequent slaking of the capillary-wetted soil in addition to the slaking and capillary-wetted pretreatments should yield a more accurate determination of the amount of stable and unstable macroaggregates. This in turn can be used to determine the aggregate-size stability distribution. This

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Abbreviations: SAI, stable aggregates index; SMaI, stable macroaggregates index.

information will improve our understanding of the dynamics of organomineral associations and soil quality and will contribute to the development of indices for improving soil management.

The objectives of this study were: (i) to develop a method for determining aggregate-size stability distribution, (ii) to develop two simple indices for soil stability based on aggregate-size stability distribution, and (iii) to test the suitability of the new method and the new indices for quantifying soil stability and for detecting differences in soil aggregate stability under different riparian plant communities.

MATERIALS AND METHODS

Field Sampling

We collected soils in September 1997 from different riparian plant communities. The communities were a cool-season grass filter, an existing riparian forest, a 7-yr switchgrass (*Panicum virgatum* L.) buffer, and a nonbuffered row cropped area in Central Iowa. Dominant grass species in the cool-season grass sites were smooth brome (*Bromus inermis* Leysser), timothy (*Phleum pratense* L.), and Kentucky bluegrass (*Poa pratensis* L.). The crop fields were under an annual maize (*Zea mays* L.)–soybean [*Glycine max* (L) Merr.] rotation. Table 1 shows a summary of the main characteristics of the soils under each of the riparian plant communities.

These riparian plant communities are examples of the standard practice conservation filters (USDA-NRCS, 1997) and are located in the Bear Creek, Long Dick Branch, and Keigley Branch watersheds in north central Iowa, USA. The experimental design was a randomized complete block with three field replicates. Treatment plots within field replicates were from 7 by 20 m to 10 by 20 m. Soil cores were taken with a 8-cm diam. steel-coring bit to a depth of 15 cm.

We collected 10 cores per plot; the exact horizontal location along the width of the plot for each core was randomly located. To eliminate edge effects we established a 0.50-m buffer zone along the edge of each plot.

Aggregate Separations

Aggregate-size fractions were isolated by wet sieving using air-dry 8-mm sieved soil. Two 100-g subsamples of air-dried soil were used to analyze the aggregate-size stability distribution. Two pretreatments are applied before wet sieving: air drying followed by rapid immersion in water (slaked) and air drying plus capillary rewetting to field capacity plus 5% (capillary-wetted) (Six et al., 1998). Both subsamples were stored overnight in a refrigerator at 4°C before wet sieving.

Aggregates were physically separated in four aggregate-size fractions: (i) large macroaggregates >2000 μm in diameter, (ii) small macroaggregates between 250 and 2000 μm in diameter, (iii) microaggregates between 53 and 250 μm in diameter, and (iv) the mineral fraction <53 μm in diameter. After wet sieving, all the fractions were oven-dried at 70°C, except the large and small macroaggregates obtained by the capillary-wetted pretreatment. These macroaggregates were air dried and later used for the separation of large and small stable macroaggregates. Sand corrections were performed by subtracting the total sand content of each size fraction from the amount of sample retained on each size fraction. The total sand content of each aggregate-size fraction was determined by weighing the material that was retained on the sieve with a 53-μm screen upon dispersal of the aggregates with sodium hexametaphosphate (5 g L^{-1}). Sand correction is needed to put on similar footing soil samples with different amounts of total sand. Sand content introduces undesirable effects on the measurement of aggregate distribution and structural stability of the soil (see Appendix).

Determination of the Aggregate Size-Stability Distribution

The experimental procedure used to determine the aggregate-size stability distribution is shown in Fig. 1. This procedure involves the slaked and capillary-wetted pretreatments; and a subsequent slaking treatment of aggregates >250 μm in size. Theoretical considerations needed for the determination of the aggregate-size stability distribution are given below.

The determination of aggregate-size stability distribution involves the assumptions that soil aggregates can be categorized in terms of their size and water stability. Therefore:

1. Soil aggregates with diameters >250 μm are labeled macroaggregates.
2. Macroaggregates are categorized as large macroaggregates when their diameters are >2000 μm (Fraction 1) and small macroaggregates when their diameters range between 250 and 2000 μm (Fraction 2).
3. Macroaggregates are also categorized in terms of their resistance to slaking. Macroaggregates that survive slaking are labeled as stable and those that do not survive are labeled as unstable.
4. Microaggregates have diameters ranging between 53 and 250 μm (Fraction 3).
5. The mineral fraction (silt + clay) has diameters <53 μm (Fraction 4).

Slaked Pretreatment Variables Definition

Variables and aggregate pathways during the slaking pretreatment are represented symbolically in Fig. 2.

1. The total amount of aggregates collected in Fraction 1 are labeled as T_{1S} and are stable large macroaggregates (S_1); $T_{1S} = S_1$.
2. The total amount of aggregates collected in Fraction 2 are labeled as T_{2S}, and are the small macroaggregates that survive slaking but with two different origins, the stable small macroaggregates that were in Fraction 2 before slaking (S_2) and the stable small macroaggregates that resulted from the fragmentation of unstable large macroaggregates upon slaking (G_2); $T_{2S} = S_2 + G_2$.

Table 1. General characteristics of the experimental field sites and surface soil (0–15 cm) properties along Bear Creek, Long Dick Branch and Keigley Branch watersheds in North Central Iowa, USA.

Site	Taxonomic classification	Texture	Total C
			g kg^{-1}
Cool-season grass filter	fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	loam	33
Existing riparian forest	fine-loamy, mixed, superactive, mesic Cumulic Haplaqudolls/ fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	sandy loam loam	25
7-yr switchgrass filter	fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	loam	21
Cropped system	fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	loam	21

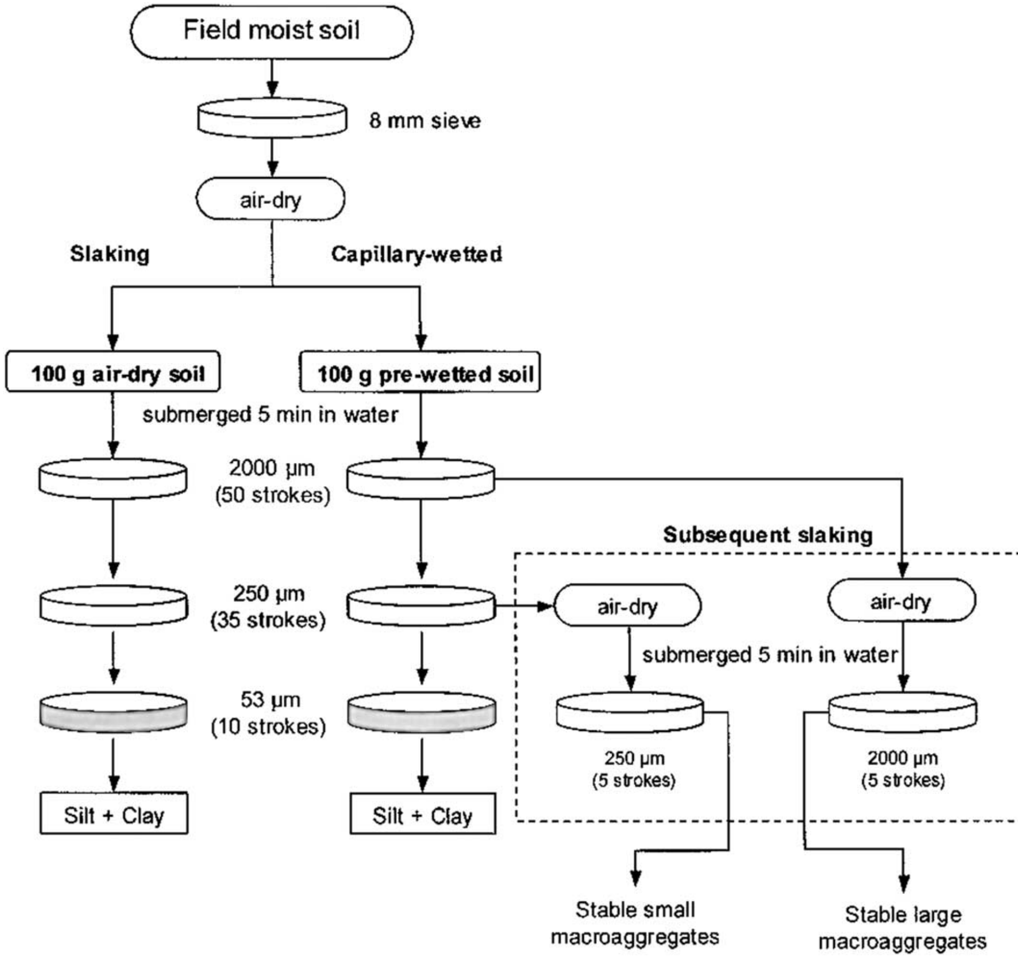

Fig. 1. Experimental procedure used to assess aggregate-size stability distribution.

3. The total amount of aggregates collected in fraction three are labeled as T_{3S} and they are microaggregates with two different origins; microaggregates that were in fraction three before slaking (S_3) and microaggregates that resulted from the disruption of unstable macroaggregates upon slaking in either Fractions 1 and/or 2, are labeled (G_3); $T_{3S} = S_3 + G_3$.
4. Finally, the material collected in Fraction 4 is the mineral fraction T_{4S}, with two different origins; mineral fraction that was in Fraction 4 before slaking (S_4) and mineral fraction that resulted from the fragmentation of unstable macroaggregates upon slaking from all previous fractions, are labeled (G_4); $T_{4S} = S_4 + G_4$.
5. The summation of the amount of aggregates collected in each size fraction after slaking should be equal to the total amount of soil (T) used for this study; $T = T_{1S} + T_{2S} + T_{3S} + T_{4S}$.

Capillary-Wetted Pretreatment Variables Definition

Variables and aggregate pathways during the capillary-wetted pretreatment are represented symbolically in Fig. 3.

1. The total amount of aggregates collected in Fraction 1 will be labeled as T_{1CW} and are the stable large macroaggregates (S_1) and the unstable large macroaggregates (U_1); $T_{1CW} = S_1 + U_1$.
2. The total amount of aggregates collected in Fraction 2 are labeled as T_{2CW} and are the stable small macroaggregates (S_2) and the unstable small macroaggregates in this fraction (U_2); $T_{2CW} = S_2 + U_2$.
3. The aggregates collected in Fraction 3 are labeled as T_{3CW} and are the microaggregates that could be found in this fraction before major perturbation of Fractions 1 and 2; $T_{3CW} = S_3$.
4. The mineral fraction collected in Fraction 4 is labeled as T_{4CW} and is the mineral fraction that could be found before major perturbation of Fractions 1 and 2; $T_{4CW} = S_4$.
5. The total summation of the amount collected in each size class after the capillary-wetted pretreatment should be equal to the whole amount of soil (T) used for this study; $T = T_{1CW} + T_{2CW} + T_{3CW} + T_{4CW}$.

Subsequent-Slaked Variables Definition

In addition to the slaked and capillary-wetted pretreatment, we physically separated the amount of stable macroaggregates in Fraction 1 and 2 from the unstable macroaggregates by performing a second slaking treatment (Fig. 1). We will refer this second slaking treatment as subsequent-slaked to differentiate this treatment from the slaked treatment (air-dry soil) initially performed to one set of the subsamples and to emphasize that it is after capillary-wetting, wet-sieving, and air drying that this second slaking is performed. The subsequent-slaked treatment was performed based on the protocol suggested by the USDA (the slake test) to assess stability of the soil when exposed to rapid wetting (USDA, 1998; Herrick, 1998). In addition, to following the USDA protocol we weighed the amount of aggregates that remained in the sieve after the subsequent slaking. The expected outcome from the subsequent slaked treatment is represented symbolically in Fig. 3.

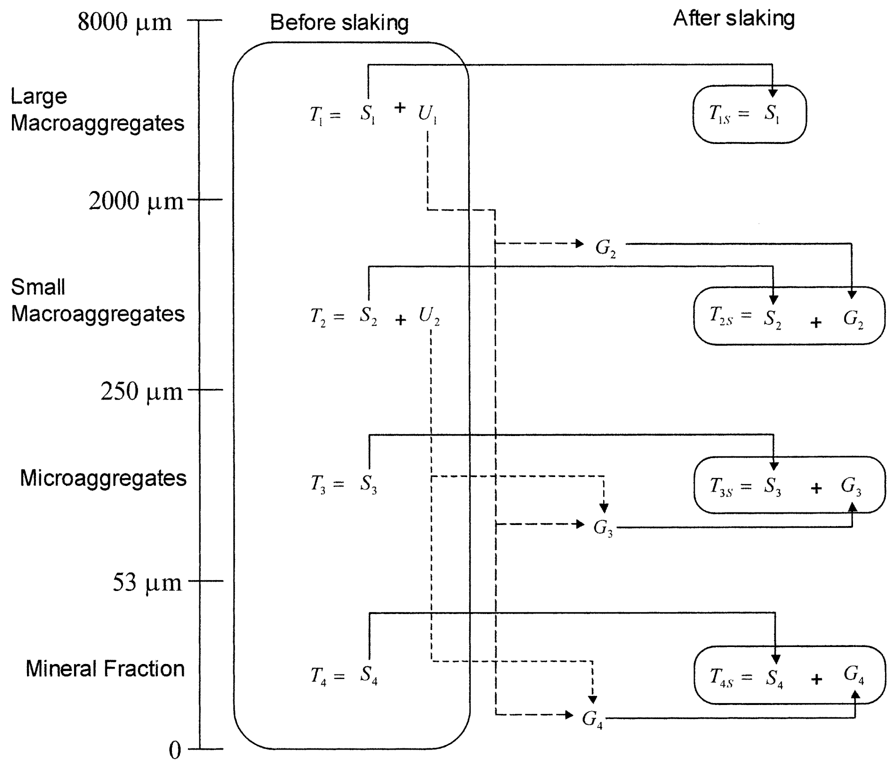

Fig. 2. Movement of aggregates during the slaking pretreatment. S = stable aggregates, U = unstable aggregates, G = gain in aggregates from other fractions, T_i = total amount of aggregates in fraction i, and T_{is} = total amount of aggregates in fraction i after slaking.

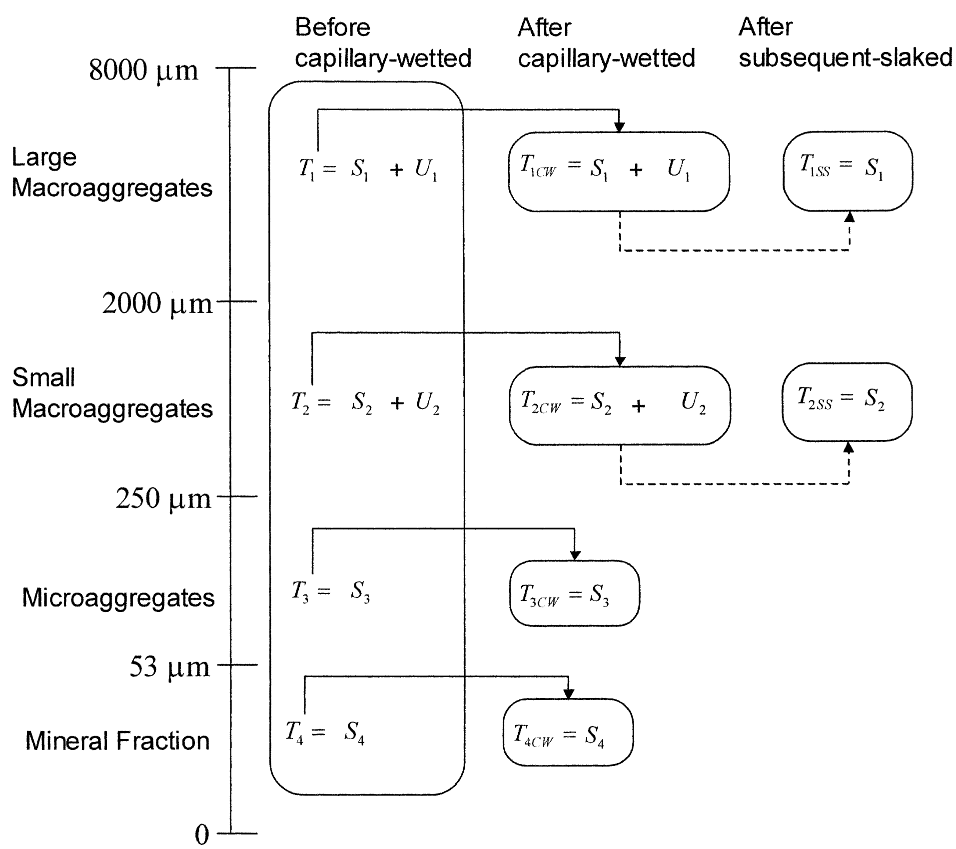

Fig. 3. General pathways involved during the capillary-wetted and the subsequent-slaked treatments. S = stable aggregates, U = unstable aggregates, T_i = total amount of aggregates in fraction i, T_{iCW} = total amount of aggregates in fraction i after capillary-wetted pretreatment T_{iSS} = total amount of aggregates in fraction i after subsequent slaked treatment.

1. The total amount of aggregates collected in Fraction 1 after the subsequent-slaked will be labeled as T_{1SS} and are the stable large macroaggregates (S_1).
2. The total amount of aggregates collected in Fraction 2 after the subsequent-slaked are labeled as T_{2SS} and are the stable small macroaggregates (S_2).

Statistical Analysis

Differences among plants communities were tested by one-way ANOVA. We used contrast test to determine significant differences with a significance level of $P < 0.05$ (ANOVA-GLM, SAS Institute, 1990).

RESULTS AND DISCUSSION

Determination of Stable and Unstable Macroaggregates

The quantity of unstable large macroaggregates can be calculated by subtracting the amount of stable large macroaggregates produced by the slaking treatment from the total amount of large macroaggregates produced by the capillary-wetted treatment; $U_1 + T_{1CW} - T_{1S}$, (Table 2). Because of the disruption of unstable large-macroaggregates upon slaking, this subtraction cannot be used for size class two. The subtraction of the slaking result from the capillary-wetted result in Fraction 2 renders a value that is associated with the difference between the amount of unstable small macroaggregates and the amount of stable small macroaggregates that are gained in size Fraction 2, (Eq. [1]). Recall that T_{2CW} and T_{2S} were defined above and they are rewritten in Eq. [2] and [3].

$$|T_{2CW} - T_{2S}| = |U_2 - G_2| \quad [1]$$

$$T_{2CW} = S_2 + U_2 \quad [2]$$

$$T_{2S} = S_2 + G_2 \quad [3]$$

The determination of S_2 and U_2 is not straightforward. The lack of information impairs the explicit calculation of the amount of stable small macroaggregates and the amount of unstable small macroaggregates. There are three unknowns S_2, U_2, and G_2 and only two equations, Eq. [2] and [3]. The dilemma of the unknowns S_2, U_2, and G_2 could be overcome if we could determine the value of any of the three unknowns. One potential candidate is S_2, which could be estimated by performing a subsequent-slaking of the aggregates collected in Fraction 2 after the initial capillary-wetted pretreatment. We will label the result of the subsequent-slaking as T_{2SS} to differentiate this from the result of the slaking treatment T_{2S}. The result of this subsequent slaking should be only stable small macroaggregates with $T_{2SS} = S_2$, (Table 2). Upon the determination of S_2 we can use Eq. [2] and [3] to calculate U_2 and G_2.

One key point in the determination of S_2 using the subsequent-slaking treatment is the implicit hypothesis that the amount of stable and unstable aggregates does not change after the physical separation using the capillary-wetted treatment following another air-drying of the aggregates overnight. This hypothesis is supported by Kemper and Rosenau (1984) who studied soil cohesion as affected by time and water content. They found that the rate of change in cohesion is slower in air-dry soils and the mechanism of strengthening and weakening the bonding between particles is either lengthy cementing and diffusive processes or lengthy dispersion processes. As a result, we do not expect major changes in the amount of stable and unstable aggregates after the capillary-wetted pretreatment. Experimentally we tested this hypothesis by performing a subsequent-slaking on 30 samples of macroaggregates collected in Fraction 1 following the capillary-wetted pretreatment. We found that the amount of large macroaggregates that survive the subsequent-slaking (T_{1SS}) was highly correlated ($r^2 = 0.96$) with the amount of large macroaggregates that survived the slaking pretreatment, (T_{1S}) for the four field sites (Fig. 4). In summary, the determination of the amount of stable and unstable aggregates involves the use of three treatments as is outlined in Fig. 1 and the set of equations summarized in Table 2.

Method Evaluation

To test the method for determining the aggregate-size stability distribution we evaluated four different field sites with different types of vegetation. Table 3 presents results after using the approach outlined above. The distribution of soil aggregates among the different size fractions was significantly influenced by the vegetation type. The amount of large macroaggregates (>2000 μm) followed the order; cool-season grass > existing riparian forest > switchgrass = cropped system. The results in Table 3 indicate that about 17% of the soil dry weight was present as stable large macroaggregates under cool-season grass, 10% under existing riparian forest, 3% under 7-yr old switchgrass, and 2% under cropped system.

Table 2. Summary of the equations used to determine the aggregate-size stability distribution; S = stable aggregates, U = unstable aggregates, G = gain in aggregates from other fractions, TS = total percentage of stable aggregates, TU = total percentage of unstable aggregates, and TG = total gain in aggregates from other fractions; T = total percentage of soil aggregates, T_{iS} = total amount of aggregates in fraction i after the slaked pretreatment, T_{iSS} = total amount of aggregates in fraction i after the subsequent slaked treatment, T = total amount of aggregates in fraction i after the capillary-wetted pretreatment.

Size fraction	Stable aggregates	Unstable aggregates	Gains
μm			
>2000	$S_1 = T_{1S}$	$U_1 = T_{1CW} - T_{1S}$	
250–2000	$S_2 = T_{2SS}$	$U_2 = T_{2CW} - T_{2SS}$	$G_2 = T_{2S} - T_{2SS}$
53–250	$S_3 = T_{3CW}$		$G_3 = T_{3S} - T_{3CW}$
<53	$S_4 = T_{4CW}$		$G_4 = T_{4S} - T_{4CW}$
Totals	TS = $S_1 + S_2 + S_3 + S_4$	TU = $U_1 + U_2$	TG = $G_2 + G_3 + G_4$
Equations to be checked	TS + TU = T	TU = TG	
Experimental test	$T_{1SS} = S_1$		

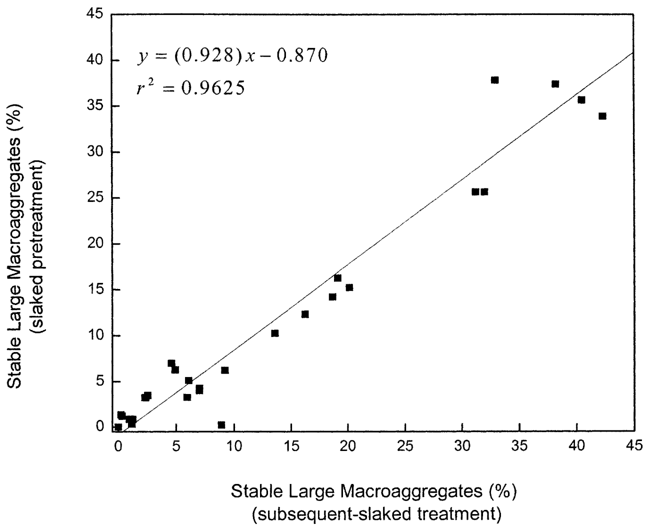

Fig. 4. Relationship between the mass of large macroaggregates >2000 μm quantified by slaked pretreatment (T_{1s}) and stable large macroaggregates >2000 μm quantified by the subsequent-slaking treatment (T_{1ss}). Values are expressed as percentages of soil dry and on a sand-free basis.

In addition, cool-season grass showed significant differences in the distribution of small macroaggregates (250–2000 μm) compared with the other vegetation types. There were no significant differences in the distribution of microaggregates (53–250 μm) under the vegetation types.

The amount of unstable macroaggregates (>250 μm) followed the order; cropped system > switchgrass = existing riparian forest > cool-season grass. These results indicate that 28% of the soil dry weight was present as unstable macroaggregates under cropped system, 23% under 7-yr old switchgrass, 19% under existing riparian forest, and 12% under cool-season grass. These results support the hypothesis that plant communities, which include species with extensive root systems, such as cool-season grass (C3 grasses), would produce the highest levels of macroaggregation. Haynes (1993) demonstrated that a short-term (5-yr) pasture (C3 grasses) could provide more soil organic matter and increased aggregate stability. Studies conducted by Tufekcioglu et al. (1999) in the same research area as the study being reported in this paper showed that cool-season grass had significantly greater dead fine root biomass than any of the other vegetation types. In addition, Pickle (1999) found that soil under cool-season grass had the highest amount of microbial biomass, followed by 7-yr switchgrass, and the cropped system soil supported the lowest amount of microbial biomass. The reduction of large and small macroaggregates in soils under the cropped system has been clearly documented by this work. Long-term cropping decreased the length and mass of fine roots, and soil organic matter resulting in a reduction of macroaggregates (Tisdall and Oades, 1980; Cambardella and Elliott, 1992).

Table 3. The aggregate-size stability distribution under four different types of vegetation sites. Values are pooled data from 1997 and 1998 expressed as percentages of dry weight of soil and on a sand-free basis ±0.1 in each size fraction. Different letters indicate differences ($P < 0.05$) between vegetation treatments within size classes. TS is the total percentage of stable aggregates and TU is the total percentage of unstable aggregates. TG is the total gain in aggregates from other fractions. *T* is total percentage of soil aggregates *T* = TS + TU.

	Water pretreatments			Aggregate-size stability distribution		
Size fraction	Slaked	Capillary-wetted	Subsequent-slaked	Stable	Unstable	Gains
μm	% dry weight of soil and on a sand-free basis					
			Cool-season grass			
>2000	16.8 (28.7)†	25.4 (46.1)		16.8a	8.6a	
250–2000	19.6 (39.4)	18.1 (36.0)	14.6a‡	14.6a	3.4a	5.0
53–250	12.9 (25.8)	7.0 (14.4)		7.0a		5.9
<53	5.1 (5.1)	3.0 (3.0)		3.0a		2.1
Total	54.4 (99.0)	53.5 (99.5)		TS = 41.4	TU = 12.0a	TG = 13.9
				T = TS + TU = 53.4		
			Existing riparian forest			
>2000	9.5 (18.3)	24.3 (46.4)		9.5b	14.8b	
250–2000	21.5 (40.7)	14.0 (29.9)	9.8b	9.8b	4.1a	11.6
53–250	10.0 (30.8)	6.4 (16.8)		6.4a		3.6
<53	9.4 (9.4)	6.0 (6.0)		6.0b		3.4
Total	50.4 (99.2)	50.7 (99.1)		TS = 31.7	TU = 18.9b	TG = 18.6
				T = TS + TU = 50.6		
			7-yr switchgrass			
>2000	2.8 (7.3)	22.4 (45.5)		2.8c	19.6c	
250–2000	20.3 (52.3)	14.5 (38.3)	11.0b	11.0b	3.5a	9.3
53–250	13.2 (28.6)	6.6 (10.1)		6.6a		6.6
<53	11.2 (11.2)	4.8 (5.5)		4.8a		6.4
Total	47.5 (99.4)	48.3 (99.4)		TS = 25.2	TU = 23.1b	TG = 22.3
				T = TS + TU = 48.3		
			Cropped system			
>2000	2.1 (3.8)	23.5 (42.8)		2.1c	21.3c	
250–2000	22.4 (41.3)	18.0 (35.1)	11.0b	11.0b	7.0b	11.4
53–250	14.0 (38.6)	5.2 (14.4)		5.2a		8.8
<53	15.3 (15.3)	7.2 (7.2)		7.2b		8.1
Total	53.8 (99.0)	53.9 (99.5)		TS = 25.5	TU = 28.3c	TG = 28.3
				T = TS + TU = 53.8		

† Values between parentheses are grams of dry weight of soil without sand correction.
‡ Different letters within the same size class indicate differences ($P < 0.05$) according to the contrast separation test.

Index for Soil Stability

We mentioned in the introduction that soil aggregate stability is a major factor for assessing soil quality. Table 4 shows some of the indices that have been proposed for quantitatively assessing soil stability. One common feature in these indices is the lack of a clear differentiation in the amount of stable and unstable macroaggregates. More recent indices are based on the subtraction of the mean value in the capillary-wetted pretreatment from the corresponding mean in the slaked pretreatment. Positive values are interpreted as a loss of material from the same fraction upon slaking. Negative values are interpreted as gains of material upon slaking. We have shown that misleading results emerge from using the difference between these values corresponding to Fraction 2.

The persistent search for a suitable index has evolved from simple metrics such as the mean weight diameter and water-stable aggregates to more complex and elaborate metrics such as the aggregation index and the normalized stability index (van Bavel, 1949; Kemper, 1966; USDA, 1998; van Steenbergen et al., 1991; Six et al., 2000) (Table 4).

The aggregate-size stability distribution may be used to assess soil stability. The rationale is that the amount of stable aggregates can be used as a metric for quantification and assessment of soil stability. We define the SAI as the ratio between the total weighted average of stable aggregates and the total weighted average of soil aggre-

Table 4. Summary of indices proposed for assessing soil stability. *n* is the total number of aggregate size classes.

Index	Reference/Comments
Mean Weight Diameter: $\mathrm{MWD} = \sum_{i=1}^{n} \overline{x}_i w_i$	**van Bavel (1949)** Easy to calculate (see the geometric mean diameter index for variables definition).
Geometric Mean Diameter: $\mathrm{GMD} = \exp\left[\sum_{i=1}^{n} w_i \log(\overline{x}_i) \Big/ \sum_{i=1}^{n} w_i\right]$	**Mazurak (1950)** $\overline{x}_i$ is the mean diameter of each size fraction. w_i is the proportion of the total sample weight occurring in the size fraction i. Extensive calculations.
Water Stable Aggregates: $\mathrm{WSA}(\%\ \text{of soil} > 250\ \mu\text{m}) = \dfrac{\text{weight of dry aggregates} - \text{sand})}{(\text{weight of dry soil} - \text{sand})} \times 100$	**Kemper (1966) and USDA (1998)** Useful when $G_2 = 0$; there are not stable small macroaggregates that can result from the fragmentation of unstable large macroaggregates upon slaking.
Aggregation Index: $\mathrm{AI} = 100 - \mathrm{DI}$ **Disruption Index:** $\mathrm{DI} = \dfrac{\mathrm{DV}}{\mathrm{DV}_{max}}$ $\mathrm{DV}_{max} = \dfrac{1}{n}\sum_{i=1}^{n} i\ \mathrm{DVS}_{max}$ and $\mathrm{DV} = \dfrac{1}{n}\sum_{i=1}^{n} i\ \mathrm{DVS}_i$ $\mathrm{DVS}_i = \dfrac{[(\mathrm{PW}_i - \mathrm{PW}_{io}) + \lvert \mathrm{PW}_i - \mathrm{PW}_{io} \rvert]}{2\left(100 - \sum_{j=i+1}^{n} \mathrm{PW}_{jo}\right)}$	**van Steenbergen et al. (1991)** Slaked and capillary-wetted pretreatments. Only gains are used. Normalization with respect to the maximum disruption level possible. $i = 1$ for the largest size class. PW_i and PW_{i0} are the proportion of total sample weight in size class *i* upon slaking and capillary-wetting, respectively. DVS_{max} is the absolute maximum disruption value for size class *i*.
Normalized Stability Index: $\mathrm{NSI} = 1 - \left(\dfrac{\mathrm{DL}}{\mathrm{DL}_{max}}\right)$ and $\mathrm{DL} = \dfrac{1}{n}\sum_{i=1}^{n}[(n+1) - i]\ \mathrm{DLS}_i$ $\mathrm{DLS}_i = \dfrac{\{[(P_{io} - S_{io}) - (P_i - S_i)] + \lvert (P_{io} - S_{io}) - (P_i - S_i) \rvert\}}{2(P_{io} - S_{io})}$ $\mathrm{DL}_{max} = \dfrac{1}{n}\sum_{i=1}^{n}[(n+1) - i]\ \mathrm{DLS}_i\ (\max)$ $\mathrm{DLS}_i\ (\max) = \dfrac{[(P_{io} - P_p) + \lvert (P_{io} - P_p) \rvert]}{2(P_{io} - S_{io})}$	**Six et al. (2000)** Slaked and capillary-wetted pretreatments. Correction for the aggregate-sized sand content. Normalization with respect to the maximum disruption level possible. Based on weight losses. $i = 1$ for the smallest size class. P_i and P_{i0} are the proportion of total sample weight in size class *i* upon slaking and capillary-wetting, respectively. S_i and S_{i0} are the proportions of sand with size *i* in aggregates of size *i* upon slaking and capillary wetting, respectively. P_p primary sand particle content with the same size as the aggregates size class after complete disruption of the whole soil.
Stable Aggregates and Stable Macroaggregates Index: $\mathrm{SAI} = \dfrac{\sum_{j=1}^{n}[(n+1) - j]S_j}{\sum_{j=1}^{n}[(n+1) - j]T_j}$ and $\mathrm{SMaI} = \dfrac{n\sum_{j=1}^{m}[(m+1) - j]S_j}{m\sum_{j=1}^{n}[(n+1) - j]T_j}$	**Márquez et al. (this paper)** Based on size-stability distribution. Slaked and capillary wetted pretreatments, and subsequent-slake. Total sand correction. $j = 1$ for the largest size class. m is the total number of size classes larger than 250 μm. S_j is the amount of stable aggregates in fraction *j*. T_j is total amount of aggregates in fraction *j* upon capillary-wetting.

gates including stable and unstable aggregates, Eq. [4].

$$\mathrm{SAI} = \frac{\sum_{j=1}^{n}[(n+1)-j]S_j}{\sum_{j=1}^{n}[(n+1)-j]T_j} \quad [4]$$

S_j is the amount of stable aggregates in fraction j. T_j is the total amount of aggregates in fraction j (from the capillary-wetted treatment) and n is the total number of size fractions. $J = 1$ for the largest size class.

We also define the SMaI as the ratio between the weighted average of the amount of stable macroaggregates (>250 μm) and the total weighted average of all soil aggregates, Eq. [5].

$$\mathrm{SMaI} = \frac{n\sum_{j=1}^{m}[(m+1)-j]S_j}{m\sum_{j=1}^{n}[(n+1)-j]T_j} \quad [5]$$

In these equations m is the total number of size classes >250 μm. Values for both of these indices are expressed as percentage stable aggregates per unit of dry weight of the soil.

Equation [5] can be thought of as equivalent to the definition of water-stable aggregates by Kemper (1966), and USDA (1998). The difference is that the determination of the water-stable aggregates involves either the slaked pretreatment or the capillary-wetted pretreatment and we have shown that the amount of stable small macroaggregates is overestimated by G_2 when using only the slaked pretreatment. We also have shown that one or two pretreatments are not enough to determine the aggregate-size stability distribution. Three treatments are needed to get an accurate assessment of both stable and unstable aggregate distribution, and thus a strong measure of soil stability. We also have shown that the slaked pretreatment produces an artificial redistribution of the unstable macroaggregate constituents that later are accounted for in the smaller fractions and that the capillary-wetted pretreatment gives only partial information about the distribution of the stable aggregates.

Table 5 compares the values for the indices defined in Eq. [4] and [5] with other published indices for soils under the four types of vegetation. The SAI and the SMaI show a clear trend across the four vegetation types. Both the stable aggregates and stables macroaggregates indices differed in the order cool-season grass > existing riparian forest > 7-yr switchgrass = cropped system. The similarity in aggregation between 7-yr switchgrass and the cropped system is the result of the young age of the experiment (7 yr) and the type of native warm-season grass (C4 grass) that was used to restore the area that was cropped for many years. It is interesting to note that the almost 75% of the dry weight of the soil under the cool-season grass consisted of stable aggregates while only 36% of the soil under the cropped system was stable aggregates. It is further interesting to note that much of a higher percentage of the stable aggregates under the cool-season grass were stable macroaggregates while only half of the weight of stable aggregates under the cropped system was composed of macroaggregates.

Although the values for stable aggregates and stable macroaggregates indices are significantly different for cool-season and existing riparian forest, the values of water stable aggregates using the capillary wetted pretreatment are not different. This is because the amount of aggregates (>250 μm) that survive slaking for cool-season grass and existing riparian forest are not significantly different; $S_{1S} + S_{2S}$ is equal to 36.4 and 31.0 (Table 3) for cool-season grass and existing riparian forest, respectively. While the amount of stable macroaggregates given by the aggregate-size stability distribution is significantly different; $S_1 + S_2$ is equal to 31.4 and 19.4 for cool-season grass and existing riparian forest, respectively. The key point is that the lack of differentiation of stable and unstable macroaggregates is biasing the values of water-stable aggregates using the slaked pretreatment.

The values of stable aggregates and stable macroaggregates indices, and water-stable aggregates using the slaked pretreatment are not significantly different for 7-yr switchgrass and cropped system. This is because the amounts of stable macroaggregates given by the aggregate-size stability distribution are not significantly different; $S_1 + S_2$ is equal to 13.8 and 13.1 for 7-yr switchgrass and cropped system, respectively. Similarly, the amount of aggregates (>250 μm) that survived slaking for 7-yr switchgrass and cropped system are not significantly different; $T_{1S} + T_{2S}$ is equal to 21.6 and 24.6 for 7-yr switchgrass and cropped system, respectively.

The water-stable aggregates using the capillary-wetted pretreatment did not show any clear trend across the different types of vegetation. The mean weight diameter index is questionable when the aggregate-size distribution is nonsymmetrical (Six et al., 2000). The equation mean weight diameter

$$\mathrm{MWD} = \sum_{i=1}^{n}\overline{x}_i w_i$$

Table 5. Treatment values for the stable aggregates index (SAI), stable macroaggregates index (SMaI), water stable aggregates of slaked (WSAs) and capillary-wetted (WSAcw), mean weight diameter of slaked (MWDs) and capillary-wetted (MWDcw) soils under four different types of vegetation sites.

Treatments	SAI	SMaI	WSAs	WSAcw	MWDs	MWDcw
	%				mm	
Cool-season grass	74a†	56a	67a	82a	1.98a	2.79a
Existing riparian forest	55b	37b	62a	76a	1.46b	2.73a
7-yr Switchgrass	37c	22c	48b	83a	0.83c	2.91a
Cropped system	36c	18c	46b	77a	0.71c	2.57a

† Different letters within a column indicate differences ($P < 0.05$) according to the contrast test.

also overestimates the original mean weight diameter for the slaked pretreatment when five, fairly broad, size fractions are used (Kemper and Rosenau, 1986). From Tables 3 and 5 we observed that the mean weight diameter for the slaked pretreatment is sensitive to the amount of unstable large macroaggregates. Why did this happen? We have shown that the slaking pretreatment produces a redistribution of unstable macroaggregate constituent units that, in turn, change the aggregate-size distribution that determines the mean weight diameter using the slaked pretreatment data. This is further supported by the fact that the mean weight diameter using the capillary-wetted pretreatment data did not show any clear trend across the different types of vegetation. We recall that the capillary-wetted pretreatment does not introduce any redistribution of unstable macroaggregates constituents. Therefore, the mean weight diameter using the slaked pretreatment data is mainly determined by the redistribution of unstable macroaggregate constituents rather than by the amount of unstable macroaggregates, thus, overestimating the mean weight diameter using the slaked pretreatment data. We could expect that the mean weight diameter for the slaked pretreatment would break down when we compare two soil samples with similar amounts of unstable macroaggregates but different structural composition of unstable macroaggregates (clay vs. hyphae bound aggregates). The difference in structural composition can produce different redistribution pathways for unstable macroaggregate constituents.

The Effects of Antecedent Water Content

The size distribution of aggregates obtained from wet sieving is very sensitive to the initial water content of the aggregates. Therefore, samples taken from the field without adjusting the soil moisture content to a common level can yield anomalous wet sieving results. Differences in soil water contents, resulting from variations in time or space, can lead to differences in aggregate stability that result in differences in aggregate-size distributions. If samples are handled carefully before sieving and soil water content is normalized, results are quite reproducible even for manual methods using different personnel (Elliott and Cambardella, 1991). Reproducible results are more feasible upon slaking when before the wet sieving we drive out all of the free water contained in the capillary pores (air drying). Also, reproducible results are more feasible upon capillary wetting when before the wet sieving, we drive out all of the free water contained in the capillary pores (air drying) and them slowly fill the capillary pores with free water until the field capacity plus 5% is reached (Six et al., 1998).

By air-drying the soil, the effect of antecedent water content on the reproducibility of the results is minimized. However, precipitation of inorganic binding agents is favored upon drying and increases with time of storage (Kemper and Rosenau, 1984). It has been suggested that an increase in surface acidity upon drying also increases binding between organic and particles (Caron et al., 1992). Air-drying may introduce changes in chemical or physical characteristics, which can alter stability measurements (Pojasok and Kay, 1990). Removal of physically bound water and free water contained in the capillary pores may yield new stable aggregates that would confound studies on soil aggregate stability. Some of these new stable aggregates could become unstable upon rewetting (hydration) transient stable aggregates but others will remain as stable aggregates.

The extent of the confounding effect due to new stable aggregates is also minimized by air-drying at room temperature. While, Kemper and Rosenau (1984) recognized that precipitation of inorganic binding agents is favored upon drying and increases with time of storage. They also concluded that the rate of change in cohesion is slower in air-dry soils at room temperature and the mechanism of strengthening and weakening the bonding between particles is either lengthy cementing and diffusive processes or lengthy dispersion process. Thus, Kemper and Rosenau (1984) suggested air-drying at room temperature soil samples as a means to standardize aggregates stability analysis by wet sieving methods.

An effective way to minimize the confounding effect of new stable aggregates is the subtraction of the slaked distribution from the capillary wetted distribution, the increased aggregation due to precipitation of inorganic binding agents and increased adsorption of organic onto particles is nullified (Six et al., 2000). Studying the extent of the nullifying effect of subtracting the slaked from the capillary wetted distribution we assumed: (i) there is a small amount δ_i of new stable aggregates in fraction i upon air-drying and upon slaking and (ii) there is a small amount δ_i^* of new aggregates in fraction i upon air-drying and upon capillary-wetted. The total amount of aggregates in fraction i after the slaked is T_{iS} and after the capillary-wetted is T_{iCW} and u_i are the amount of stable and unstable aggregates in fraction i before air-drying, respectively. g_i is the gain in aggregates from other fractions. By subtracting the slaked from the capillary wetted distribution we obtain:

$$\begin{aligned}
|T_{1CW} - T_{1S}| &= |(s_1 + \delta_1^* + u_1) - (s_1 + \delta_1)| \\
&= |u_1 + (\delta_1^* - \delta_1)| \\
|T_{2CW} - T_{2S}| &= |(s_2 + \delta_2^* + u_2) - (s_2 + \delta_2 + g_2)| \\
&= |u_2 - g_2 + (\delta_2^* - \delta_2)| \\
|T_{3CW} - T_{3S}| &= |(s_3 + \delta_3^*) - (s_3 + \delta_3 + g_3)| \\
&= |-g_3 + (\delta_3^* - \delta_3)| \\
|T_{4CW} - T_{4S}| &= |(s_4 + \delta_4^*) - (s_4 + \delta_4 + g_4)| \\
&= |-g_4 + (\delta_4^* - \delta_4)|
\end{aligned}$$

If the amount of new aggregates upon air-drying and slaking is similar to the amount of new aggregates upon air-drying and capillary-wetting then $(\delta_i^* - \delta_i) \rightarrow 0$ and there is a significant minimization of the confounding effect. However, transient new stable aggregates upon air-drying could become unstable and δ_i^* will become different from δ_i $(\delta_i^* \neq \delta_i)$. In conclusion subtracting the slaked from the rewetted aggregate distribution can potentially nullify the effect of air-drying due to the stabilization of new aggregates.

Analyzing the effect of air drying on the aggregate-size stability distribution we assumed: (i) there is a small amount δ_i of new stable aggregates in fraction *i* upon air-drying and upon slaking, (ii) there is a small amount δ_i^* of new aggregates in fraction *i* upon air-drying and upon capillary-wetted and (iii) there is a small amount of new stable aggregate δ_i^* in fraction *i* upon the subsequent air drying and prior the subsequent slaking. S_i and U_i are the amount of stable and unstable aggregates in fraction *i* upon physical separation of the aggregates, respectively. G_i is the gain in aggregates from other fractions including new aggregates that were stabilized by air-drying the soil samples. s_i and u_i are the amount of stable and unstable aggregates in fraction *i* before air-drying, respectively. g_i is the gain in aggregates from other fractions. From Table 2, we get:

$$S_1 = s_1 + (\delta_1);\ S_2 = s_2 + (\delta_2^* + \delta_2'');$$
$$S_3 = s_3 + (\delta_3^*);\ S_4 = s_4 + (\delta_4^*)$$
$$U_1 = u_1 + (\delta_1^* - \delta_1);\ U_2 = u_2 + (-\delta_2'')$$
$$G_2 = g_2 + (\delta_2^* - \delta_2'');\ G_3 = g_3 + (\delta_3 - \delta_3^*);$$
$$G_4 = g_4 + (\delta_4 - \delta_4^*)$$

Note that the amount of stable aggregates, unstable aggregates and the gains are under or over estimated depending on the extent of the stabilization of new aggregates and particularly on the values of δ_i, δ_i^*, and δ_i''. However, a good estimation of the amount of stable and unstable aggregates could be done when δ_i^* and $\delta_i \rightarrow 0$ and $\delta_i'' \rightarrow 0$. Indeed the results in Fig. 4 suggest that this is the case in our study. The high correlation (r^2 = 0.96) found between the mass of large macroaggregates quantified by slaked pretreatment (T_{1S}) and stable large macroaggregates quantified by the subsequent-slaking treatment (T_{1SS}) suggest that δ_i^* and $\delta_i \rightarrow 0$ and $\delta_i'' \rightarrow 0$. However, the four soils considered in this study represent a very narrow range of solid texture (sandy loam loam) and organic matter content (2.1–3.3% total C). Since the implicit hypothesis that the amount of stable and unstable aggregates does not change after the physical separation, δ_i^* and $\delta_i \rightarrow 0$ and $\delta_i'' \rightarrow 0$, is critical for the proposed method, it should be pointed out that the assumption may no necessary be valid for other combinations of soil type/soil management. More work needs to be done to nullify or to know the extent of the confounding effect of δ_i, δ_i^*, and δ_i''.

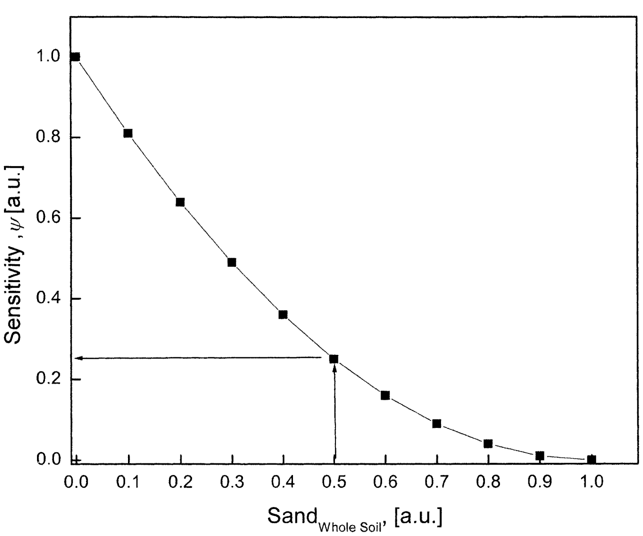

Fig. 5. Sensitivity of *f* to changes in TS/(TS + TU) as a function of the total amount of sand.

CONCLUSIONS

We developed a theoretical framework that demonstrated that the use of a subsequent slaking following the standard capillary-wetted pretreatment provides the means for an accurate determination of the aggregate-size distribution and the amount of stable and unstable macroaggregates. The amount and distribution of stable and unstable aggregates in the soil can be used as an indicator of the stabilization and destabilization of soil aggregates. These two mechanisms are closely associated with the dynamics of soil organic matter and soil quality. The stable aggregate and stable macroaggregate indices are suitable and highly sensitive to the effects of vegetation on soil stability. The SAI and the SMaI indices were higher in surface soils under cool-season grass than any of the other treatments. These soils samples are well aggregated with the weighted average of stable aggregates representing 74%, of the dry weight of the soil followed by 55% under existing riparian forest, 40% under 7-yr switchgrass and 36% under cropped system. The clearest difference was in the total amount of stable large macroaggregates (>2000 μm), which generally differed in the order cool-season grass > existing riparian forest >7-yr switchgrass = cropped system. More than three quarters of the weight of stable aggregates under the cool-season grass consisted of stable large macroaggregates while only half of the weight of the stable aggregates under the cropped system was macroaggregates. This information has strong implications for the potential infiltration capacity and aeration of the surface soils under the various vegetation communities.

Although the results in Fig. 4 indicate that the hypothesis that the amount of stable and unstable aggregates does not change after the physical separation using the capillary-wetted treatment following another air-drying of the aggregates overnight is correct, the four soils considered in this study represent a very narrow range of solid texture (sandy loam, loam) and organic matter content (2.1–3.3% total C). It should be pointed out that the assumption may not necessarily be valid for other combinations of soil type/soil management.

APPENDIX

Why Sand Correction?

Although sand plays a passive role in the formation of aggregates it is widely recognized that the application of a correction for the amount of sand is essential for interpreting results on aggregate composition and dynamics. In general, sand could be in three different forms in the soil: (i) sand that is within stable aggregates, (ii) sand that is within unstable aggregates and can easily be redistributed, and (iii) sand that is free.

During fractionation, aggregate-size classes will accumulate sand of similar diameters. The accumulated sand particles can have two origins: particles of sand that result from the destruction of macroaggregates (probably fine sand) and particles of sand that were free and not within any aggregate. The redistribution of sand following the physical separation of the aggregates (e.g., sieving) produces the so-called 'loose sand' effect (Christensen, 1996; Cambardella and Elliott, 1993b; Elliott, 1986). The redistribution of 'loose sand' produces dispersion of C in the microaggregate-size fraction ($<250\ \mu m$) and the enrichment of clay and silt in macroaggregate-sized fractions ($>250\ \mu m$). We analyzed the impact of the amount of sand in the whole soil on the sensitivity of the SAI. We used f to represent SAI without the sand correction and x to represent SAI with the sand correction. For simplicity and without losing generality, we redefined the nomenclature as shown in Eq. [6].

$$f = \frac{TS + Sand_{Stable\ Aggregates}}{TS + TU + Sand_{Whole\ Soil}} \quad \text{and}$$

$$x = \frac{TS}{TS + TU} \qquad [6]$$

In this equation TS is the total amount of stable aggregates, and TU is the total amount of unstable aggregates. $Sand_{Whole\ Soil}$ is the total amount of sand in the whole soil, and $Sand_{Stable\ Aggregates}$ is the sand associated with stable aggregates. Note that $Sand_{Stable\ Aggregates}$ represents sand within stable aggregates and free sand with diameters similar to the aggregates.

The sensitivity ψ of f to changes in x is given by Eq. [7] and is strongly dependent on the total amount of sand $Sand_{Whole\ Soil}$.

$$\psi = \frac{\partial f}{\partial x} = (1 - Sand_{Whole\ Soil})^2 \qquad [7]$$

Figure 5 shows the values of ψ as a function of $Sand_{Whole\ Soil}$. If $Sand_{Whole\ Soil} = 0.5$, then from Eq. [7] and from Fig. 5 ψ is equal to 0.25. This means that a change of four units in the value of the ratio TS/(TS + TU) could produce a relative change of one unit in f. We conclude from Fig. 5 that not using the sand correction could mislead the interpretation of the results because the total amount of sand limits the sensitivity of f to reflect real changes in the ratio TS/(TS + TU). Therefore, studying soil stability without the sand correction would mask significant differences between values of the SMaI. The application of procedures for accounting for sand content becomes essential for correctly interpreting results on aggregate composition and dynamics.

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