TEMPORAL CHANGES IN WET AGGREGATE STABILITY

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ABSTRACT

Aggregate stability, a property that influences a soil's erodibility and hydraulic characteristics, has been shown in previous investigations (e.g., Bullock et al., 1988) to vary over time for some northwestern U.S. soils. The objectives of this study were to evaluate three procedures for measuring aggregate stability and quantify variation in aggregate stability over time (that is, within a growing season) for selected soils across the United States. In 1988 and 1989, soils from 11 states were sampled monthly from April to July and in September. The stability of 1- to 4-mm aggregates from each sample was measured by 1) wetting air-dry (A-D) aggregates in a vaporizer followed by wet-sieving; 2) immersing A-D aggregates immediately prior to wet sieving; and 3) vapor-wetting field-moist aggregates followed by wet sieving. The sieving of vapor-wetted field-moist aggregates best revealed temporal variation. In general, the aggregate stability of northern soils varied more over time than did the aggregate stability of southern soils, probably due to differences in freezing and thawing. Biological activity likely accounted in part for temporal changes in the stability of soils from the upper Midwest. Trends in stability change over time in soils from one region of the United States to another were seldom similar. **KEYWORDS.** Soil properties, Aggregates, Stability.

INTRODUCTION

Aggregate stability is a measure of an aggregate's resistance to breakdown, usually measured by sieving in water. It is an important soil property because it can be related to a soil's erosion rate or its hydraulic characteristics, such as its infiltration rate. Aggregate stability (indicative of soil strength) can be measured by imparting stress to aggregates via wet sieving, controlled rates of wetting (Pierson and Mulla, 1989; 1990), or the impact of a simulated raindrop (Young, 1984). Analysis by waterdrop impact may be more indicative of an aggregate's resistance to breakdown by rainfall (interrill erosion case) while analysis by wet sieving is more indicative of resistance to breakdown in flowing water (rill erosion case). While used less commonly to study aggregate stability, the drop impact method (or some modification of it) has good potential to measure not only aggregate stability but also erodibility characteristics of soils (Nearing and Bradford, 1985; Sharma et al., 1991; Young, 1984).

It is known that aggregate stability varies for some soils over a growing season (Ellsworth et al., 1991; Perfect et al., 1990a) or even longer periods (Bullock et al., 1988). Such changes over time need to be known for soils from regions other than the Pacific Northwest so they can be accounted for in erosion prediction models or irrigation management systems. Numerous authors (e.g., Alberts et al., 1987; Karlen et al., 1990) have recently recommended additional study of temporal changes in soil properties including aggregate stability.

Temporal variation in aggregate stability and other soil surface properties affect the susceptibility of soil to both wind and water erosion (Alberts et al., 1987; Coote et al., 1988; Formanek et al., 1984). From a managerial viewpoint, knowledge of such variation could lead to improved production practices that better control erosion (Kemper et al., 1989). Changes over time in soil erodibility have been studied for a number of years (Coote et al., 1988; Mutchler and Carter, 1983; Young et al., 1990) but only recently has much interest been shown in studying temporal changes in aggregate stability (Bullock et al., 1988; Perfect et al., 1990b). Significant breakthroughs likely await detailed studies in this subject area.

Variation over time in a soil property such as aggregate stability may be caused by many factors including tillage (Schjonning and Rasmussen, 1989), climate (Coote et al., 1988; Stefanson, 1968), and biological activity (Metting, 1987; Perfect et al., 1990a). It may be that biological and physical processes operate sequentially or simultaneously. An energy source available to microorganisms (Kemper et al., 1987; Perfect and Kay, 1990; Reid and Goss, 1981) late in the growing season may help to maximize aggregate stability prior to the freezing season (Bullock et al., 1988).

Climatic processes such as freezing and thawing may be responsible in part for changes seen in aggregate stability over time. When a soil freezes, for example, liquid water moves in response to a temperature gradient toward developing ice lenses through unfrozen water films (Miller, 1980; Perfect et al., 1990c) surrounding soil particles. As this water flows, it could transport via mass flow, slightly soluble bonding agents such as silica or Ca to soil particle-to-particle contact points, there to be precipitated (Lehrsch et al., 1992; Perfect et al., 1990c). As an ice lens enlarges it imposes forces on nearby constrained aggregates, often weakening them, though at times strengthening them (Bullock et al., 1988; Lehrsch et al., 1991; Mostaghimi et al., 1988; Perfect et al., 1990c). An improved understanding of these forces and their modes of operation may permit us to

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minimize their adverse impacts on soil structure as well as maximize their beneficial impacts on soil structure.

Some of the more promising avenues of investigation involve the study of the physical, biological, and/or chemical processes responsible for observed variation in aggregate stability. Studying the freeze/thaw process, Lehrsch et al. (1991) found that soils with clay contents of 17% or more and/or organic matter contents over 3% were the most stable after freezing. Also, aggregate stability often decreased linearly with increasing water content at freezing. The stability of field-moist aggregates often increased from zero to one or three freeze-thaw cycles. Unger (1991) also found soil physical properties to improve over a relatively cold but dry winter. Over a wetter winter, however, he detected a decrease in aggregate stability (as measured by mean weight diameter). Temporal variation caused by a freeze/thaw mechanism or any other process or combination of processes is worthy of detailed study. Thus, the objectives were to 1) evaluate three procedures used to measure aggregate stability; and 2) quantify variation in aggregate stability over time, particularly within a growing season.

Methods and Materials

Aggregate stability was measured on soil samples taken from 11 states across the United States. The soils studied were: a Palouse silt loam (fine silty, mixed, mesic pachic Ultic Haploxeroll) from Pullman, Washington; two Portneuf silt loams (coarse silty, mixed, mesic Durixerollic Calciorthids) from Idaho, one from cropland near Kimberly, and one from rangeland near Hansen; a Williams sandy loam (fine loamy, mixed Typic Argiboroll) from McClusky, North Dakota; a Sverdrup sandy loam (sandy, mixed Udic Haploboroll) from Elbow Lake, Minnesota; a Barnes loam (fine loamy, mixed Udic Haploboroll) from Morris, Minnesota; a Sharpsburg silty clay (fine, montmorillonitic, mesic Typic Argiudoll) from Lincoln, Nebraska; a Grant sandy loam (fine silty, mixed, thermic Udic Argiustoll) from rangeland near Chickasha, Oklahoma; a Heiden clay (fine, montmorillonitic, thermic Udic Chromustert) from Riesel, Texas; a Grenada silt loam (fine silty, mixed, thermic Glossic Fragiudalf) from Holly Springs, Mississippi; a Tifton loamy sand (fine loamy, siliceous, thermic Plinthic Paleudult) from Tifton, Georgia; two Cecil sandy loams (clayey, kaolinitic, thermic Typic Kanhapludults), one moderately eroded and one severely eroded, from Watkinsville, Georgia; a Miami silt loam (fine loamy, mixed, mesic Typic Hapludalf) from Trotwood, Ohio; and a Caribou silt loam (coarse loamy, mixed, frigid Typic Haplorthod) from Presque Isle, Maine.

From each of these locations, quadruplicate 1.8-kg soil samples were taken from the upper 10-15 cm of a 3.2-m^2 area of each fallowed soil profile throughout the 1988 and 1989 growing seasons. Those samples, taken approximately 25 April (1989 only), 16 May, 6 June, 15 July, and 15 September, when obtained, were placed moist in air-tight, zip-lock polyethylene bags and were shipped in padded, rigid-wall containers via overnight mail to Kimberly for analysis. If the analyses could not be performed on the day the samples arrived, they were stored in their existing moist condition, chilled (at +7° C), until they could be analyzed. When the analysis could be made, each sample was split into thirds, with one subsample kept moist and the other two air-dried.

TABLE 1. Aggregate stability analytical procedures

Symbol	Description
A-D, VW	Air-dry aggregates (1-4 mm) vapor wetted to 0.30 kg kg^{-1}
A-D, DI	Air-dry aggregates (1-4 mm) directly immersed
F-M, VW	Field-moist aggregates (1-4 mm) vapor wetted to 0.30 kg kg^{-1}

Three analytical procedures (Table 1) were used to measure aggregate stability. Described in detail below, all were modifications of the standard procedure (Kemper and Rosenau, 1986). The first will be denoted with the symbol "A-D,VW" where A-D indicates air-dried aggregates and VW indicates vapor wetting, the second with "A-D,DI" where DI indicates direct immersion, and the third with "F-M,VW" where F-M indicates field-moist aggregates. To compare the three procedures, aggregates with diameters of 1-4 mm (best for the F-M,VW procedure, see below) were analyzed. In all methods, after the aggregates were wetted, they were sieved in distilled water for 5 min in 1988 and for 3 min in 1989. A 3-min sieving was used in 1989 to match as closely as possible the standard procedure. The two fewer minutes of wet sieving in 1989 caused little change, with the measured aggregate stabilities being greater by approximately 4.6 percentage points, on average, than they would have been if sieved for 5 min. Aggregate stability was reported as the weight percent of aggregates that remained stable after wet sieving. Concretions were considered sand particles with diameters greater than 0.26 mm.

The three procedures differed primarily in the pre-wetting step. In the A-D,VW method, very similar to the standard, air-dry aggregates (usually 1-2 mm but here 1-4 mm) were wetted over a 30-min period to 0.30 kg kg^{-1} using a non-heating vaporizer (Humidifier Model No. 240, Hankscraft, Reedsburg, WI) prior to wet sieving. Aggregates from soils in the more humid eastern United States are quite stable when they are wet slowly prior to wet sieving (Kemper and Koch, 1966). As a consequence, their high stabilities make it difficult to detect the effects of cropping systems, for example, or cropping histories on aggregate stability. Because those air-dry aggregates were so strong, the A-D,DI procedure was used to impart a greater disruptive force by directly immersing them in water and then immediately wet sieving them. The air-drying common to the first two procedures imparts additional strength to aggregates (Reid and Goss, 1981) and makes interpretation more difficult. To overcome this difficulty in the F-M,VW procedure, the aggregates were not air-dried but rather sieved field-moist. To measure their aggregate stability, one's thumb and forefinger gently broke the moist clods into <4 mm aggregates (too much additional pressure was needed to break them into <2 mm). After the 1-4 mm aggregates were obtained by sieving, they were vapor-wetted to 0.30 kg kg^{-1} and wet sieved. After a few oscillations in distilled water, the larger aggregates commonly broke to the 1- to 2-mm size.

Statistical analyses were performed on arcsin $(x)^{0.5}$ -transformed data (to stabilize variance) using an analysis of variance (SAS Institute, Inc., 1985). In all figures, the mean with its confidence interval, ±2 standard deviations, was plotted for each procedure on each sampling date. Some means were not plotted because the samples were lost. Within a procedure, transformed means from adjacent dates were considered to be statistically different from one another if their confidence intervals did not overlap.

Results and Discussion

Analysis of the 1988 and 1989 samples of a Palouse silt loam from Washington state revealed that the A-D,VW aggregates exhibited the highest stabilities over 1.3 on the transformed scale (approx. 93% without transformation, fig. 1). The A-D,DI aggregates, on the other hand, exhibited the lowest stabilities, usually ranging from 0.4 to 0.6 (15 to 32%). These lower stabilities are reasonable because the direct immersion procedure applies to the aggregates the greatest disruptive force due to air entrapment within the aggregates as they are immersed just prior to wet sieving. Aggregate stability measured on field-moist aggregates was intermediate between the values measured using the two other methods. Stabilities measured using the three procedures were commonly ranked as A-D,VW > F-M,VW > A-D,DI.

The trend in the response of the aggregates was similar when the aggregates were analyzed using the F-M,VW and the A-D,DI procedures but the changes from sampling date to sampling date were greater when the F-M,VW procedure was employed (fig. 1). The air-drying of aggregates in the A-D,DI procedure (as well as in the A-D,VW procedure) apparently masked some of the variation in aggregate stability from sampling date to sampling date by strengthening the (often less stable) wet aggregates more than the relatively dry aggregates. Lehrsch et al. (1991) suspected that air-drying masked some aggregate stability variation caused by the freeze/thaw process. For the Palouse silt loam in 1988, F-M,VW aggregate stabilities (on the transformed scale) varied by a factor of two. Ellsworth et al. (1991) studying Minnesota soils in crop production, also detected changes of a similar magnitude. Because of the high sensitivity of the F-M,VW method, statistically significant differences were detected in aggregate stability for the Palouse silt loam from the June-July and from the July-September samplings for both years (fig. 1). For the 1989 samples, using the A-D,DI procedure, we also found those differences to be statistically significant. In contrast, the A-D,VW method identified no temporal variation in either 1988 or 1989.

From June through September 1988 and from April through July 1989, Palouse aggregate stability (when measured using either the F-M,VW or A-D,DI procedure) usually steadily increased (fig. 1). This same response was seen in the Williams sandy loam at McClusky, North Dakota (data not shown), and in other soils of the intermountain region of the Pacific Northwest (Bullock et al., 1988). This trend, at times referred to as a recovery phenomenon, could have been caused by the precipitation of slightly soluble bonding agents at the points of contact between soil particles (Kemper and Rosenau, 1984). These bonding agents could have included carbonates of calcium and magnesium, gypsum, silica, or in more southern locales, iron, aluminum, and/or manganese oxides (Harris et al., 1966; Martin et al., 1955). The precipitation of these bonding agents at the points of contact would have been a consequence of the slow drying that occurred in these soils over these months (Table 2) and often occurs in many soils from spring to fall (Mutchler and Carter, 1983).

A soil's temporal variation revealed by either the F-M,VW or A-D,DI procedure at times differed from 1988 to 1989. For example, the stability of Palouse aggregates increased from July to September 1988, but analysis of the 1989 soil samples revealed that it decreased for the same time period the following year (fig. 1). Unger (1991) also found overwinter soil physical property changes to differ from winter to winter.

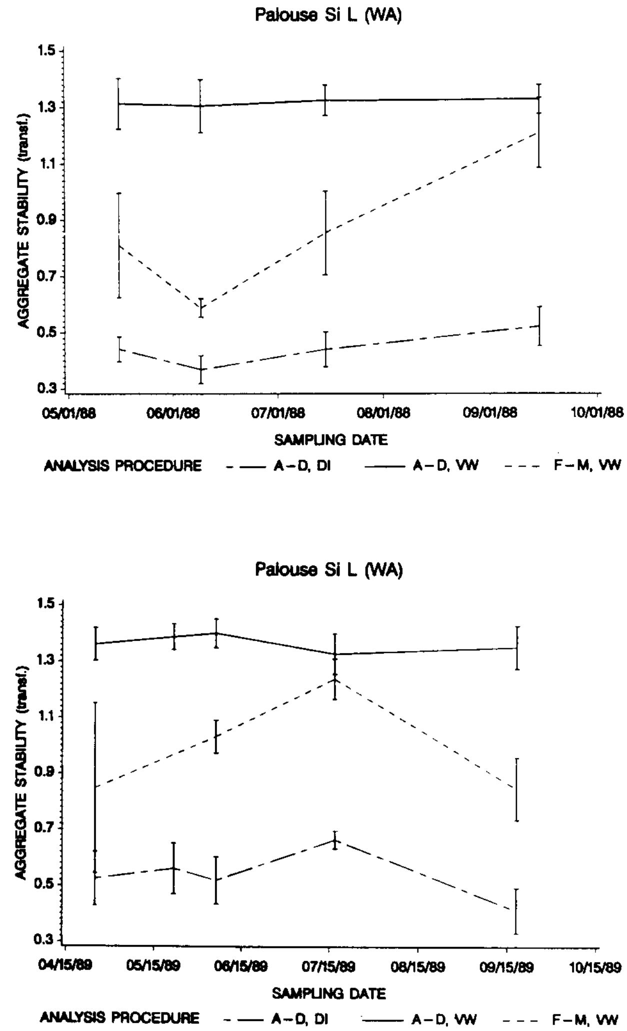

Figure 1–Aggregate stability as a function of time for a Palouse silt loam in 1988 and 1989.

These differences in response from year to year are likely due to different climatic factors, such as rainfall, temperature, or frost occurrence. In this study, the water contents of the field-moist soil samples (Table 2) were, in general, indirectly proportional to the aggregate stabilities measured using the F-M,VW procedure and, to a lesser degree, the A-D,DI procedure. Many investigators (Alberts et al., 1987; Coote et al., 1988; Ellsworth et al., 1991; Perfect et al., 1990a; Truman et al., 1990) have also found temporal changes in aggregate stability to be strongly related to water content differences.

As noted earlier, differences in aggregate stability from one sampling date to another were commonly greatest when the F-M,VW procedure was used to measure aggregate stability (fig. 1). To obtain a quantitative measure of each analysis procedure's "power", that is, the sensitivity with which each procedure could detect statistically significant differences in a soil's aggregate stability from date to date, a statistical analysis was performed on the data from the entire study. This quantitative measure of each procedure's

TABLE 2. Water contents of field-moist samples of six soils in 1988 and 1989

Soil Series	Water Content*								
	1988				1989				
	May	Jun	Jul	Sep	Apr	May	Jun	Jul	Sep
	kg kg^{-1}								
Barnes	0.14	0.08	0.08	0.20	0.15	0.15	0.14	0.20	0.16
Grenada	0.17	0.10	0.19	0.17	0.25	0.21	0.17	0.24	0.24
Heiden	0.15	0.23	0.24	0.10	0.15	0.12	0.22	0.16	0.20
Palouse	0.15	0.21	0.18	0.07	0.13	0.14	0.15	0.03	0.19
Sverdrup	0.04	0.01	0.04	0.11	0.08	0.04	0.07	0.08	0.07
Williams	0.17	0.14	0.10	0.08	0.17	0.15	0.17	0.11	0.21

* Average of four replications.

sensitivity was a ratio of the variance between sampling dates to the sum of the variances between sampling dates and within each date. Specifically, the statistic was the R^2 from a one-way analysis of variance with sampling date as the sole source of variation in the model. These sensitivity statistics revealed that the F-M,VW method was the most sensitive in over 60% of the cases (Table 3). The A-D,DI method was most sensitive in 25% of the cases while the A-D,VW method proved the most sensitive in just over 14% of the cases. Thus, to study temporal variation in aggregate stability for many soils with widely different characteristics, the F-M, VW method is still recommended (Lehrsch and Jolley, 1989).

In general, northern soils exhibited more temporal variation than did southern soils (from Oklahoma, Texas, Mississippi, and Georgia). For example, in 1988 the stability of field-moist aggregates of the Palouse in Washington (fig. 1) varied from about 0.59 to 1.24 (31-89%) while, for a Heiden clay in Texas (fig. 2), field-moist aggregate stabilities ranged only from about 1.28 to 1.45 (92-99%). Changes in water content, noted above to be indirectly proportional to aggregate stability, do not account for the variation of the Palouse being greater than that of the Heiden because the changes in water content were the same (0.14 kg kg^{-1}) for both soils (Table 2). Greater variation in aggregate stability over time for northern soils may have been due to more occurrences of freezing and thawing (Bullock et al., 1988; Harris et al., 1966; Mostaghimi et al., 1988; Perfect et al., 1990b) in northern than southern locales. Other factors or processes that may cause soils to respond differently could include temperature and water content (Alberts et al., 1987; Coote et al., 1988; Perfect et al., 1990a) and/or microbiological activity (Harris et al., 1966; Martin et al., 1955; Metting, 1987). For cropped soils, additional causative factors could be composition of added organic material (Martin et al., 1955; Perfect et al., 1990b), residue decomposition rate (Stefanson, 1968), and tillage (Schjonning and Rasmussen, 1989). While the 1988 stability variation in the Heiden clay was slight (fig. 2), the F-M,VW procedure still detected statistically significant differences from May to June and from July to September.

As noted earlier, soils from the South exhibited less temporal fluctuation in aggregate stability than did soils from the North. Southern soils, when they did vary in stability over time, often displayed a trend exemplified by the Grenada silt loam in 1988 (fig. 3). After increasing early in the summer, aggregate stability often decreased consistently through September. Stefanson (1968; 1971) observed similar trends in the stability of some Australian soil aggregates.

TABLE 3. Analytical procedure sensitivity to temporal variation in aggregate stability

Soil Type	Sensitivity*					
	1988			1989		
	A-D, VW	A-D, DI	F-M, VW	A-D,VW	A-D, DI	F-M, VW
Barnes loam	0.50	0.88	0.99	0.80	0.19	0.78
Caribou silt loam	0.86	0.93	0.87	-	-	-
Cecil sandy loam (mod. eroded)	0.35	0.47	0.86	0.79	0.68	0.86
Cecil sandy loam (sev. eroded)	0.78	0.83	0.95	0.05	0.11	0.66
Grant sandy loam (rangeland)	0.76	0.66	0.88	0.69	0.83	0.91
Grenada silt loam	0.64	0.85	0.93	0.85	0.85	0.75
Heiden clay	0.59	0.92	0.96	0.41	0.57	0.51
Miami silt loam	0.90	0.83	0.29	0.45	0.72	0.84
Palouse silt loam	0.08	0.83	0.94	0.48	0.84	0.83
Portneuf silt loam (cropland)	0.90	0.78	0.48	0.51	0.95	0.25
Portneuf silt loam (rangelend)	0.33	0.13	0.73	0.83	0.26	0.89
Sharpsburg silty clay	0.43	0.60	0.21	0.89	0.43	0.75
Sverdrup sandy loam	0.46	0.79	0.94	0.35	0.78	0.73
Tifton loamy sand	0.68	0.41	0.87	-	-	-
Williams sandy loam	0.29	0.14	0.91	0.44	0.68	0.83

* The ratio of the variance between sampling dates to the sum of the variances between sampling dates and within each sampling date. Each value was the R^2 from a one-way analysis of variance with sampling date as the sole source of variation in the model.

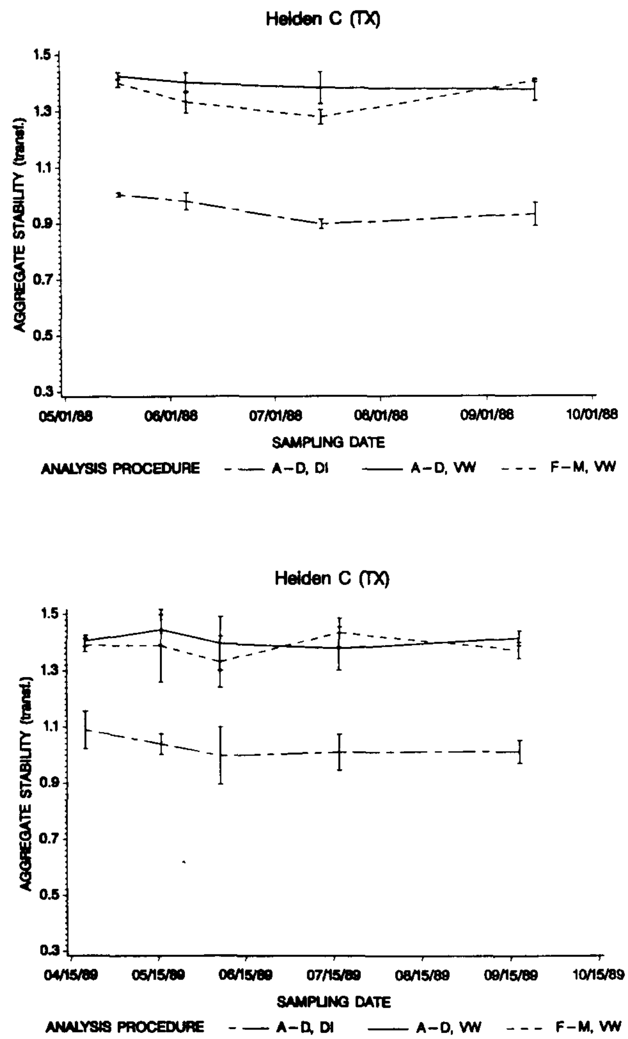

Figure 2–Aggregate stability as a function of time for a Heiden clay in 1988 and 1989.

Microbiological activity may have been responsible for the increase then decrease in stability (fig. 3). In the spring and early summer, the soil dried somewhat (Table 2) but more importantly would have warmed, encouraging microbial breakdown of plant residues and microbiological production of polysaccharides and other organic compounds known to stabilize aggregates (Harris et al., 1966). Coote et al. (1988) found field-moist aggregate stabilities to be proportional to temperature increases, or more specifically degree days. As the growing season progressed, easily decomposable, carbonaceous material from plant residues may have become limiting. Microbes then would have begun decomposing polysaccharides and other similar aggregate-stabilizing materials (Harris et al., 1966; Martin et al., 1955). This destruction of stabilizing agents would then account for the decrease in aggregate stability often observed as the growing season passed (fig. 3). Young et al. (1990) noted that differences in microbial activity and breakdown of organic compounds were factors responsible for temporal changes in aggregate stability.

In west central Minnesota, changes over time in the stability of field-moist aggregates of a Sverdrup sandy loam were much like changes seen in aggregates of a Barnes loam (fig. 4). Though differing widely in texture as well as pH and organic matter (data not shown), geographically the soils were separated by less than 50 km. Climate, as it no doubt affected soil water content, may have caused similar temporal changes in the aggregate stability of these soils from the same region. Indeed, data from 1989 (not shown) revealed that these two soils again responded similarly, though the 1989 trend over time in aggregate stability was different from that observed in 1988. Other data (not shown) provide additional evidence that climatic differences more than soil property differences influence aggregate stability variation over time.

The significant decrease in aggregate stability for the Barnes loam from July to September 1988 (fig. 4) may be indicative of soil erosion trends in Minnesota. Young et al. (1990) presented both measured and predicted soil erodibilities (USLE K factors) for the Barnes loam that increased from the end of the growing season to the occurrence of complete soil freezing. Since some (e.g., Luk, 1979) have found aggregate stability to be indirectly proportional to soil erodibility, the data of figure 4 showing a decrease in stability in the late summer of 1988 may provide, in part, an explanation for the observed increase in erodibility in the fall. The timing of the 1988 decrease in aggregate stability and the increase in erodibility reported by Young et al. (1990) are not, however, an exact match. This discrepancy could be due to the 1988 climatic conditions departing somewhat in timing from the long-term average. Kemper et al. (1989) also presented evidence that temporal variation in aggregate stability helps to explain seasonal variation in soil erodibility.

Summary and Conclusions

Soils from northern areas, particularly the Northwest and upper Midwest, generally exhibited the most temporal variation in aggregate stability. For northwestern soils, temporal variation may be caused by chemical processes, such as the precipitation of some chemical specie, and/or by physical processes, such as freezing and thawing. For naturally more stable soils from the upper Midwest or the humid East, biological processes may additionally play an important role in aggregate stability variation over time.

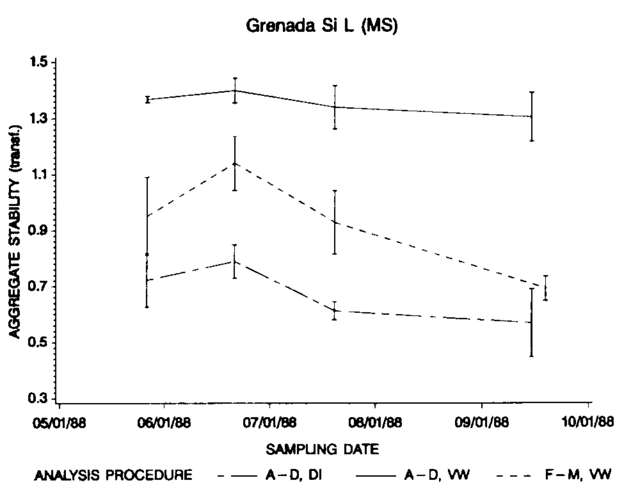

Figure 3–Aggregate stability as a function of time for a Grenada silt loam in 1988.

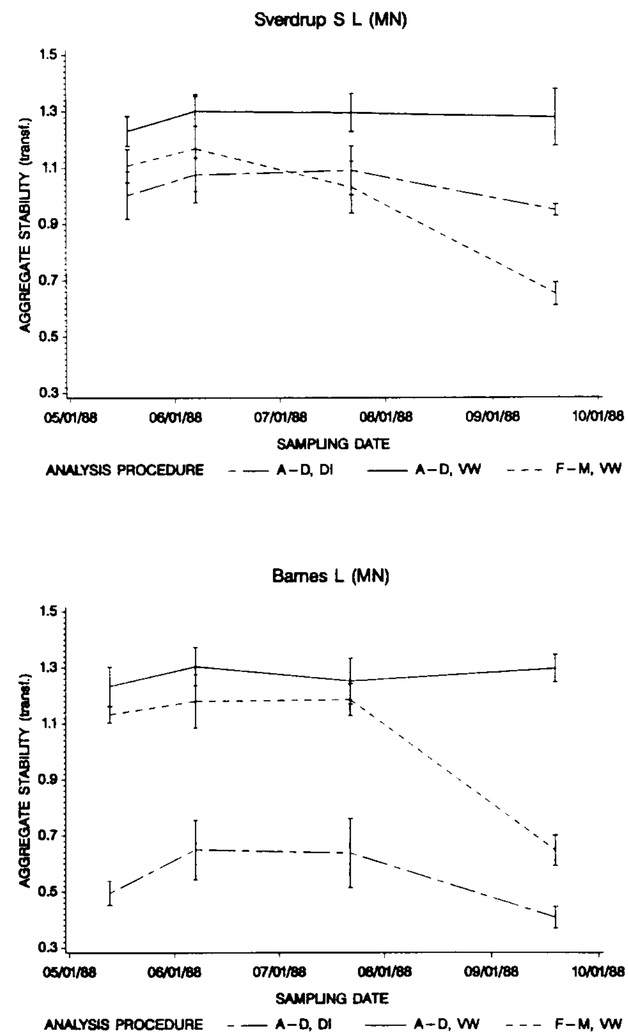

Figure 4–Aggregate stability as a function of time for a Sverdrup sandy loam and a Barnes loam in 1988.

From this study, we conclude 1) the analysis of field-moist, vapor-wetted aggregates best revealed temporal variation in aggregate stability; 2) within a growing season aggregate stability varied, at times by a factor of two, over time; and 3) trends of change over time in aggregate stability differed from one geographic region to another and from the 1988 growing season to the 1989 growing season.

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