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Aggregate Stability Response to Freeze-Thaw Cycles

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ABSTRACT

Research has suggested that 1 to 3 freeze-thaw cycles (FTCs) may increase the stability of soil aggregates, when field-moist aggregates are wet sieved. The objectives of this laboratory experiment were to quantify aggregate stability of relatively wet aggregates from the Ap horizons of four soils when subjected to either 0, 1, 2, or 4 FTCs and, secondly, to identify a threshold number of FTCs for each soil below which aggregate stability increases. Moist soil was packed into 28-mm-diam., 50-mm-tall brass cylinders by tapping to a dry bulk density of 1.15 Mg m^{-3}, sealed in polyethylene bags, then slowly frozen convectively at -5°C for 48 h, then thawed at +6°C for 48 h for each FTC. The first 1 to 2 FTCs in general increased aggregate stability, but additional FTCs had little effect. For 3 of 4 soils, 2 to 3 FTCs appeared to increase aggregate stability to a plateau or threshold. FTCs increased aggregate stability, when averaged across the four soils, more in the 0- to 15-mm depth increment than in the 15- to 30-mm increment.

Key words: Freezing, thawing, soil physical properties, wet sieving, soil depth

INTRODUCTION

Aggregate stability is an important soil property because soil susceptibility to water and wind erosion increases, in part, as aggregate stability decreases (Lehrsch 1995, Luk 1979). Soils with relatively unstable aggregates can seal readily with rain or irrigation and, upon drying, form crusts easily. Sealing reduces infiltration and increases runoff whereas crusting hinders seedling emergence (Lehrsch 1995). Both processes impair crop production.

Wet aggregate stability is a dynamic property. Both management factors and climatic processes cause stability to vary temporally (Lehrsch 1995). Management factors include tillage, irrigation, and crop residue management. Climatic processes include precipitation (wetting), evaporation (drying), freezing, and thawing. In temperate regions, freezing and thawing cause stability to vary greatly (Bullock et al. 1988, Lehrsch et al. 1991, Mostaghimi et al. 1988, Staricka and Benoit 1995). In many areas subject to freezing, wind and water erosion can occur in the spring before vegetation covers clean-tilled fields. If surface soil aggregates were to enter the winter relatively stable, though they would be weakened somewhat by winter freezing (Lehrsch and Jolley 1992), they could nonetheless better resist breakdown and movement from these erosive forces in the spring.

Wet aggregate stability can also increase under some conditions. For example, soil drying during periods of low rainfall or in soil near and below enlarging ice lenses (Czurda et al. 1995) can precipitate cementing or bonding agents like $CaCO_3$, silica, gypsum or iron oxides at contact points between primary particles or smaller aggregates. This precipitation often enables aggregates to withstand subsequent disruption by water (Kemper et al. 1987, Lehrsch et al. 1991, Perfect et al. 1990). Drying both gathers and arranges clay domains at contacts between sand and silt particles, increasing aggregate stability (Lehrsch 1995, Rowell and Dillon 1972).

Aggregate stability can be decreased by freeze-drying aggregates on or near the soil surface (Staricka and Benoit 1995) and, in general, by freeze-thaw cycles. Ice lenses that form and enlarge during freezing

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likely cause potential fracture planes to develop in nearby aggregates (Lehrsch et al. 1991). Failure along these planes of weakness is likely responsible for the reduced stability and weakened structure of relatively wet, mineral soils that undergo many FTCs (Benoit 1973, Hinman and Bisal 1968, Mostaghimi et al. 1988). Results from some studies (Bisal and Nielsen 1964, Lehrsch et al. 1991) have suggested, however, that there may be a relatively small number of FTCs, up to about four, during which stability may increase. Unfortunately, where not protected by residue, vegetative cover, or snow, aggregates in the uppermost 30 mm of many south-central Idaho soil profiles may freeze and thaw 30 to 40 times from fall to spring (J.L. Wright 1996, personal communication). Through these seasons, aggregates at the soil surface may freeze and thaw at cycles ranging from diurnal to weekly, or longer (Hershfield 1974).

Management practices may be modified to control, somewhat, the FTCs that surface aggregates are subjected to. Wheat (*Triticum aestivum* L.) stubble, rather than being plowed after harvest, may be left standing to mulch the surface and reduce the number of subsequent freeze-thaw events (Pikul and Allmaras 1985). Standing stubble would also trap snow to insulate the soil and, in dryland cropping regions, lead to increased water storage in the profile. Crop residue from minimum tillage production systems, or organic materials from manure applications, on the soil surface may also lessen the number of FTCs that surface aggregates experience.

This laboratory study was both a follow-up to and extension of two earlier studies (Lehrsch et al. 1991 and 1993). In this study, the freezing chamber was held at -5°C (Lehrsch et al. 1992, Rowell and Dillon 1972) to slowly freeze the soil, thereby permitting water redistribution as the soil froze. To better measure treatments effects on stability, aggregates from shallow (15-mm) layers were analyzed, as recommended by Cary (1992). In this study, all soil samples when frozen contained water at the same matric potential, -33 kPa. In earlier studies, due in part to logistical constraints, we were unable to adequately study changes that occurred in the stability of relatively wet aggregates subjected to 1, 2, and 4 FTCs. Recent findings (Lehrsch et al. 1991) suggest, however, that we need to better understand how moist aggregates respond to just a few FTCs. Thus, this experiment was designed to i) quantify the aggregate stability response of relatively wet, field-moist aggregates from four continental U.S. soils, two differing primarily in clay content and two in organic C, to up to 4 FTCs and ii) identify a threshold number of FTCs for each soil below which aggregate stability increased.

MATERIALS AND METHODS

The study was conducted as a three-factor experiment with a factorial arrangement of two factors, soils and freeze-thaw cycles, laid out in a randomized complete block design. The third factor was sampling depth, either 0-15 or 15-30 mm. It was modeled as a subplot treatment (or repeated measure) for each combination of the first two factors. Each treatment was replicated six times. Ap horizons of four soils were studied: a Barnes loam (*Udic Haploboroll*) from Morris, Minnesota, a Sharpsburg silty clay (*Typic Argiudoll*) from Lincoln, Nebraska, a Palouse silt loam (*Pachic Ultic Haploxeroll*) from Pullman, Washington, and a Portneuf silt loam (*Durixerollic Calciorthid*) from Kimberly, Idaho. Some index properties of the four soils are given in Table 1. The Barnes, Palouse, and Portneuf soil samples were taken from fallowed fields in the spring of 1988. After the Barnes and Palouse samples were air mailed to Kimberly, samples of all three soils were stored, field-moist, in air tight containers at +6°C until used. The Sharpsburg sample was taken in May of 1996 from a field planted to winter wheat, shipped to Kimberly, and stored as were the other soils until used.

All soils were field-moist (initial water contents ranged from 0.12 to 0.14 kg kg^{-1}, Table 1) and sieved through a 4-mm sieve prior to packing. Just before the <4-mm fraction of each soil was packed, its water content was slowly raised by vapor-wetting until its soil water was at a matric potential of −33 kPa (according to water contents given by Elliot et al. 1989). Water contents at that potential ranged from 0.22 to 0.27 kg kg^{-1} (Table 1).

The sample handling and preparation procedures were nearly identical to those reported in Lehrsch et al. (1991). In brief, tapping was used to pack moistened soil, to a dry bulk density of 1.15 Mg m^{-3}, into brass cylinders 50 mm tall with inside diameters of 28 mm. Each packed cylinder was then sealed in a Ziploc[1], polyethylene bag to inhibit water loss and prevent later freeze-drying, and placed into a cavity in a polystyrene foam tray. The foam, at least 70 mm beneath and 20 mm beside each cylinder, served as insulation so that freezing occurred primarily downward from the surface. The packed samples were then subjected to either 0, 1, 2, or 4 FTCs. The 0-cycle samples were not frozen. The packed soil for the other cycles was then slowly frozen, convectively and without access to additional water, at −5°C (plus or minus 1°C) for 48 h,

[1]Mention of trade names is for the reader's benefit and does not imply endorsement of the products by the USDA.

Table 1. Soil properties.

Soil type	Particle size distribution Sand	Silt	Clay	COLE†	Base sat.	Exch. Ca	CEC	Org. C	Initial agg. stab.‡	Water content Field-moist	When packed§
	(g kg^{-1})			(cm cm^{-1})	(%)	(cmol kg^{-1})		(g kg^{-1})	(%)	(kg kg^{-1})	
Barnes loam	490	340	170	0.030	100	-	19.5	16.0	35	0.14	0.22
Sharpsburg silty clay	30	560	410	0.086	94	19.4	29.4	13.3	85	0.12	0.27
Palouse silt loam	100	700	200	0.026	82	12.7	19.6	13.2	87	0.13	0.26
Portneuf silt loam	220	660	120	0.012	100	-	12.6	9.9	46	0.14	0.25

†Coefficient of linear extensibility.
‡Measured on the stored soil about 90 days before the experiment was performed.
§Equal to the water content at a matric potential of −33 kPa.

then thawed at +6°C (plus or minus 1°C) for 48 h for each freeze-thaw cycle. A data logger and thermocouple within each freezing chamber recorded ambient air temperatures. After the appropriate samples had been frozen for the last time and had thawed for 48 h, they were brought to room temperature by resting on a lab bench for 2 h. Each sample was then removed from its cylinder and sectioned to obtain samples from 0-15 and 15-30 mm. The samples from each layer were not air-dried but immediately sieved gently, by hand, to obtain moist, 1- to 4-mm aggregates. Four g of these were then vapor-wetted to 0.30 kg kg^{-1} within 30 min using a non-heating vaporizer (Humidifier No. 240, Hankscraft[1], Reedsburg, Wisconsin). Immediately thereafter, the aggregates were sieved in distilled water for three min to measure aggregate stability (Kemper and Rosenau 1986, as modified by Lehrsch et al. 1991). The principal modification was that field-moist 1- to 4-mm aggregates, rather than air-dry 1- to 2-mm aggregates, were vapor-wetted before sieving. Analyses of variance were performed using SAS (SAS Institute Inc. 1989)[1]. A broad inference analysis was conducted to broaden the scope of applicability. In such an analysis, the variation between replications was included as part of the error term used to determine whether soils, FTCs, or their interaction significantly affected aggregate stability. In the analysis of variance, probabilities ≤ 0.105 were considered statistically significant.

RESULTS AND DISCUSSION

Analysis of variance

A Bartlett's test indicated that not all treatment variances were statistically equal. Upon examination, the variances for Palouse, cycle 0, depths 0-15 and 15-30 mm averaged 163 while the variances of the remaining 30 treatment combinations averaged 44. Since no transformation was found to equalize such disparate variances, a weighted analysis of variance (AOV) was performed, using as weights the reciprocals of these two average variances. When compared to the results from a non-weighted AOV, the results from the weighted AOV differed little. The residuals from fitting the statistical model using a weighted analysis exhibited a mean of 0 and were normally distributed (Shapiro-Wilk W= 0.984, P= 0.634). The weighted AOV revealed that aggregate stability was affected by a pair of two-way interactions: one between soils and FTCs (P= 0.001) and the other between sampling depths and FTCs (P= 0.104).

Interaction between soils and freeze-thaw cycles

FTC effects upon aggregate stability were soil-dependent. Increasing FTCs tended to increase each soil's aggregate stability, when averaged across both sampling depths (Fig. 1). The stability increase, from 0 to 1 FTC, was significant for Barnes (P<0.001) and

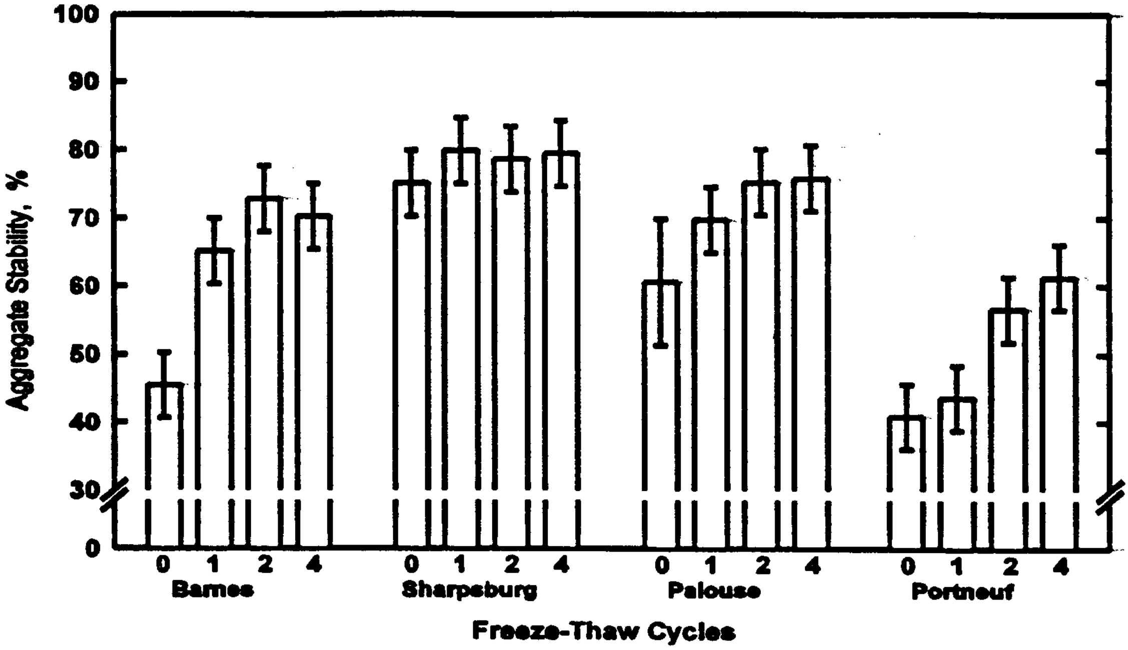

Figure 1. Aggregate stability of each soil measured at each freeze-thaw cycle, averaged across sampling depths. Each mean (n = *12) is shown with its 95% confidence limits.*

Palouse (P= 0.085). Perfect et al. (1990) also reported wet aggregate stability to increase after just one FTC. From 1 to 2 FTCs, the increase was significant for Barnes (P= 0.028) and Portneuf (P<0.001). No other adjacent FTC means within each soil differed at a probability of less than 0.100. The Sharpsburg soil, with 410 g clay kg^{-1}, was the only soil that did not show a significant response from any one FTC level to an adjacent one. Its aggregate stability stabilized at about 79%, however, from 1 to 4 FTCs.

This increase in stability of field-moist aggregates with particularly the first 1 or 2 FTCs (Fig. 1) was considered by Lehrsch et al. (1991) to be a normal or common response. Lehrsch et al. (1993) described a process that could cause these increases. In brief, ice formation in inter-aggregate pores or ice lens enlargement could bring nearby soil particles into contact. Slightly soluble, inorganic bonding agents would then move or, to minimize their potential energy, diffuse to those contact points (Kemper et al. 1987). Once there, the bonding agents would precipitate, thereby increasing the aggregate's stability, as the soil dried due to freezing-induced soil water redistribution (Czurda et al. 1995, Kemper et al. 1987, Perfect et al. 1990). Since this precipitation was likely irreversible (Kemper et al. 1987), these bonding agents did not re-enter the soil solution during subsequent thawing periods. As FTCs accrued, more of the bonding agents that had remained in solution in the unfrozen water films surrounding soil particles during previous freezing episodes likely precipitated from the soil solution, further strengthening the aggregates. This precipitation mechanism may explain the increase in aggregate stability with the first few FTCs. Freezing and ice formation have been reported (Bisal and Nielsen 1964, Czurda et al. 1995, Perfect et al. 1990, Rowell and Dillon 1972) to improve aggregation and increase aggregate stability. In the frozen samples in my experiment, neither ice lenses nor frost heaving were observed. Some ice crystals were seen, however, on the soil surfaces. Initial tests revealed that, within the packed cylinders, freezing caused little detectable vertical water redistribution.

Aggregate stability differed little, for most soils, from 2 to 4 FTCs (Fig. 1). Portneuf stability changed (increased) the most, from 56.6 to 61.3%, though significant only at P= 0.175. These minimal changes that occurred after 2 FTCs support the view that either a threshold or possibly a plateau was reached after just two to four FTCs. Only the Barnes decreased in stability from 2 to 4 FTCs (though again significant only at P= 0.453). Mostaghimi et al. (1988), who wet sieved air-dried aggregates, found Barnes' aggregate stability to decrease sharply from 3 to 6 FTCs.

The data in Fig. 1 suggest that the aggregate stability of the Barnes and Palouse soils reached a plateau, or possibly a threshold, from 2 to 4 FTCs. To statistically test this tentative finding, a trend analysis was performed (Table 2). It confirmed that the Barnes' and Palouse's aggregate stability responded in a curvilinear (that is, quadratic) manner to increasing FTCs.

Table 2. Trend analysis of freeze-thaw cycle effects on aggregate stability.

Trend	Significance			
	Barnes	Sharpsburg	Palouse	Portneuf
Linear	**†	NS	**	**
Quad-ratic	**	NS	*	NS

† *, ** Significant at the 0.05 and 0.01 probability levels, respectively.

The responses, fitted to data averaged across both depths, were:

$$AS_{Bar} = 46.0+21.8(FTC)-3.9(FTC)^2 \quad (R^2=0.79) \quad [1]$$

and

$$AS_{Pal} = 60.6+10.8(FTC)-1.8(FTC)^2 \quad (R^2=0.42) \quad [2]$$

where AS was aggregate stability, expressed as a percentage, and FTC was the number of freeze-thaw cycles experienced. Equations [1] and [2] indicate that each soil's aggregate stability would be greatest just before or at 3 FTCs. The Portneuf was the only soil of the four we studied whose aggregate stability responded linearly (i.e., linear trend significant but quadratic not) to FTCs. Its response was:

$$AS_{Por} = 41.0+5.5(FTC) \qquad (R^2=0.70) \qquad [3]$$

Numerous findings in this experiment were similar to those reported by Lehrsch et al. (1991, 1993). The stability of field-moist aggregates of Barnes loam increased with the first 2 or 3 FTCs. After Sharpsburg aggregates were frozen and thawed at least once, their stability was about 80% and did not significantly change thereafter with accruing FTCs. Palouse aggregates, when frozen at water contents ranging from 0.26 to 0.30 kg kg^{-1}, exhibited a monotonic increase in stability through 4 or 5 FTCs. The stability of the Portneuf changed little from 0 to 1 FTC. In this experiment, however, its stability from 1 to 2 FTCs increased from 43.6 to 56.6% (significant at $P<0.001$). I have no explanation, other than that given above, for this highly significant 13 percentage-point increase.

Interaction between sampling depths and freeze-thaw cycles

FTC effects upon aggregate stability, averaged across four soils, differed from one depth to the other (Fig. 2). A trend analysis performed on the data shown in Fig. 2 confirmed ($P<0.001$) that, at each depth, aggregate stability responded curvilinearly to freeze-thaw cycles. The fitted responses were:

$$AS_{0\text{-}15} = 56.9+13.2(FTC)-2.2(FTC)^2 \quad (R^2=0.87) \quad [4]$$

and

$$AS_{15\text{-}30} = 53.9+9.1(FTC)-1.4(FTC)^2 \quad (R^2=0.64) \quad [5]$$

Eqns. [4] and [5] also indicate that, at each depth, aggregate stability would be greatest at 3 or just more than 3 FTCs.

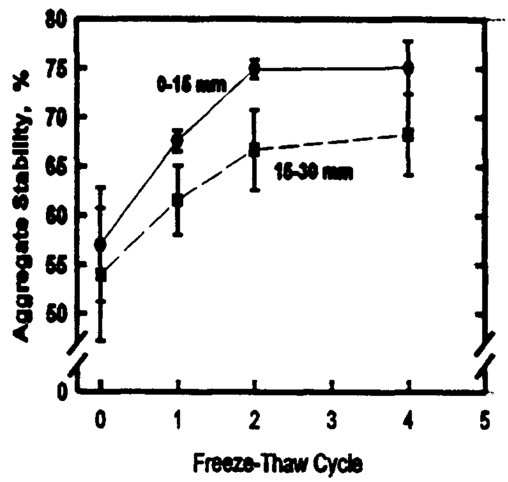

Figure 2. Freeze-thaw cycle effects on aggregate stability, averaged across four soils, measured at each sampling depth. Each mean (n = *6) is shown with its 95% confidence limits.*

At each level of FTC, aggregate stability at 0-15 mm exceeded that at 15-30 mm (Fig. 2). The data also reveal that these differences increased with each cycle through 2 FTCs. For all soils averaged across all FTCs, aggregate stability at 0-15 mm, 68.6%, was nearly 10% greater (significant at $P<0.001$) than at 15-30 mm, 62.6%.

The data in Fig. 2 also reveal that, with each FTC up to two, aggregate stability increased more near the surface than below it. Aggregates near the surface experienced less overburden pressure or, in other words, were less constrained from moving about. Unconstrained aggregates are more stable than constrained aggregates after freezing (Bullock et al. 1988, Lehrsch et al. 1991). These differences in stability with depth at each FTC were, however, relatively small, generally less than seven percentage points. Fall plowing or rototilling to reduce surface bulk density to maximize any aggregate stability increase with FTCs is not recommended.

Aggregate stability at each depth increased most with the first FTC (Fig. 2). In both the 0-15 and 15-30 mm layers, the increase in aggregate stability per unit increase in FTC decreased with increasing FTCs. This finding supports the view that slightly soluble bonding agents were being removed from the soil solution by being precipitated at intra-aggregate contact points (Kemper et al. 1987, Lehrsch et al. 1991). Most would likely have been precipitated with the first FTC. Thereafter, only those bonding agents that had remained in solution during previous freezes could have been precipitated (Lehrsch et al. 1991). Thus, progressively less strengthening of aggregates would have occurred as FTCs accrued. The data shown in Fig. 2 support this precipitation hypothesis.

Regardless of depth, aggregate stability of field-moist aggregates increased with the first two FTCs (Fig. 2). Eqns. [1], [2], [4], and [5] predict aggregate stability to be greatest near 3 FTCs. These findings suggest that, if possible, land managers should allow soils to freeze two or three times in the fall to increase their stability and, thus, resistance to wind and water erosion. Alternatively, managers could minimize the FTCs that surface soil experiences by, for example, establishing winter cover crops or adopting minimum tillage production systems to increase crop residues on the soil surface. Any practice that would better insulate the soil should help stabilize surface aggregates. Data in Fig. 2 also show that aggregate stability changed little from 2 to 4 FTCs, regardless of depth. With more FTCs, aggregate stability would likely decrease (Benoit 1973, Mostaghimi et al. 1988).

Organic C and clay effects on aggregate stability

In a related study conducted earlier (Lehrsch et al. 1991), soils that differed in organic C and those that differed in clay content responded differently to freezing and thawing. When slowly frozen, as in this experiment, relatively wet aggregates from those same soils may not have responded in the same manner. The two soils differing in organic C and the two differing in clay content were thus compared. Because the soil by cycle interaction (Fig. 1), was significant ($P<0.001$), comparisons were made at each level of FTC. The Palouse, with 33% more organic C than the Portneuf (Table 1), was significantly more stable than the Portneuf at each level of FTC. In contrast, the stability of the Sharpsburg, with more than twice the clay of the Barnes (Table 1), was significantly more stable than the Barnes only at FTC levels of 0 and 1. Higher clay contents, possibly related to clay aggregate formation (Rowell and Dillon 1972) or clay bridging between sand and silt particles (Kemper et al. 1987), appear to some way strengthen aggregates after FTCs of 0 and 1 but not after 2 or more. During the first FTC, dispersed clay may move about (Rowell and Dillon 1972) and lodge in low potential energy resting places within aggregates, imparting little additional stability to those aggregates with subsequent FTCs.

Additional studies could be conducted to identify the physical and/or chemical constituents that may be i) moving into or out of each soil layer (Perfect et al. 1990), and ii) causing the aggregate stability changes observed in this study, as well as others (Lehrsch et al. 1991, 1993). Any additional studies should focus on only one or two soils (e.g., Palouse and Portneuf) and add a sodium silicate and/or 2 g kg^{-1} $CaSO_4$ treatment (Lehrsch et al. 1993). Larger cylinders should be used so that a larger sample will be retrieved from each shallow depth increment. In this larger sample, investigators should measure aggregate stability and water dispersible clay (Pojasok and Kay 1990) and analyze a number of chemical constituents, including soluble Ca, soluble silica, organic C, and polysaccharides. If a suitable extraction and analysis procedure can be developed, soluble organic carbon should also be measured on selected treatments, particularly to compare soils with quite different (high and low) organic C contents. Experimenters should consider using the model ICE-1 (El-Kadi and Cary 1990) to estimate water flow and water redistribution during freezing to assist in interpreting their findings.

CONCLUSIONS

The stability of wet-sieved, field-moist aggregates of Barnes, Palouse, and Portneuf soils increased with 1 and/or 2 FTCs. From 2 to 4 FTCs, little additional change occurred. The stability of Sharpsburg silty clay aggregates was not significantly affected by FTCs. For all soils but the Portneuf, 2 to 3 FTCs appeared to increase stability to a plateau or threshold. FTCs increased aggregate stability more at 0-15 than 15-30 mm. Averaged across soils at each depth, stability increased more with the first than the second FTC.

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