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FREEZE-THAW CYCLES INCREASE NEAR-SURFACE AGGREGATE STABILITY

Gary A. Lehrsch

Soils with stable surface aggregates resist water and wind erosion better than soils with unstable aggregates. From earlier studies, we had preliminary evidence that one to three freeze-thaw cycles (FTCs) increased soil aggregate stability when measured by wet sieving field-moist aggregates. In this study, we measured the stability of aggregates vapor-wetted to field capacity from the Ap horizons of four soils after undergoing either zero, one, two, or four FTCs, and we determined the number of FTCs at which aggregate stability would be greatest for each soil. Moist soil was packed to a dry bulk density of 1.15 Mg m^{-3} by tapping it into 28-mm-diameter, 50-mm-tall brass cylinders. Each cylinder was then sealed in a polyethylene bag and inserted into a polystyrene foam tray. The soil in each cylinder was frozen convectively at −5°C for 48 h and then thawed at +6°C for 48 h for each FTC. Aggregate stability increased with the first one to two FTCs but changed little thereafter. Trend analysis revealed that aggregate stability would be greatest after two or three FTCs. When averaged across the four soils, FTCs stabilized aggregates more at 0 to 15 mm than at 15 to 30 mm. Near the surface of wet soils, two or three FTCs may be beneficial rather than detrimental to soil structure. (Soil Science 1998;163:63–70)

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

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 unstable aggregates can seal readily with rain or irrigation and, upon drying, form crusts. Sealing reduces infiltration and increases runoff, whereas crusting hinders seedling emergence (Lehrsch 1995). Both processes impair crop production. Aggregates that undergo many freeze-thaw cycles (FTCs) (5 to 10 or more) are known to become less stable (Benoit 1973; Edwards 1991; Mostaghimi et al. 1988). Aggregates that experience fewer FTCs, however, may not respond in the same way.

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 occur in the spring before vegetation covers clean-tilled fields. If surface soil aggregates enter the winter in relatively stable condition, they may be weakened somewhat by winter freezing (Lehrsch and Jolley 1992), but they will be more capable of resisting breakdown and movement from these erosive forces in the spring.

Wet aggregate stability can increase under some conditions. For example, soil drying (i) during periods of low rainfall or (ii) near and below enlarging ice lenses (Czurda et al. 1995) can precipitate cementing or bonding agents such as $CaCO_3$, 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.

USDA-Agricultural Research Service, Northwest Irrigation and Soils Research Laboratory, 3793 N. 3600 E., Kimberly, ID 83341-5076. E-mail: Lehrsch@kimberly.ars.pn.usbr.gov

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1987; Lehrsch et al. 1991; Perfect et al. 1990). Drying both gathers and arranges clay domains at contacts between sand and silt particles, thus increasing aggregate stability (Lehrsch 1995; Rowell and Dillon 1972).

Aggregate stability can also 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 are presumed to cause potential fracture planes to develop in nearby aggregates (Lehrsch et al. 1991). Failure along these planes of weakness is probably responsible for the reduced stability and weakened structure of relatively wet mineral soils that undergo many FTCs (Benoit 1973; Edwards 1991; Hinman and Bisal 1968; Mostaghimi et al. 1988). Results from some studies (Bisal and Nielsen 1964; Lehrsch et al. 1991), however, have suggested that a small number of FTCs, up to about four, may cause stability to 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). Throughout these seasons, aggregates at the soil surface may freeze and thaw at cycles ranging from hourly to weekly or longer (Hershfield 1974).

Management practices may be modified to exert some control over the FTCs to which surface aggregates are subjected. Rather than plowing wheat (*Triticum aestivum* L.) stubble after harvest, it may be left standing to mulch the surface and reduce subsequent freezing and thawing (Pikul and Allmaras 1985). Standing stubble or rough soil surfaces 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 an extension of two earlier studies (Lehrsch et al. 1991, 1993). In those investigations, the stability of field-moist aggregates of medium- and fine-textured soils frequently increased, at times significantly, from zero to one FTC. Findings from those studies revealed the need to understand better how aggregates at water contents near field capacity on or near the soil surface respond to the first few FTCs. Thus, this experiment was designed to (i) measure the stability of field-moist aggregates from four continental U.S., soils wetted to water contents near field capacity, after undergoing up to four FTCs, and (ii) determine the number of FTCs at which aggregate stability would be greatest for each soil.

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 to 15 or 15 to 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, MN, a Sharpsburg silty clay (*Typic Argiudoll*) from Lincoln, NE, a Palouse silty clay loam (*Pachic Ultic Haploxeroll*) from Pullman, WA, and a Portneuf silt loam (*Durixerollic Calciorthid*) from Kimberly, ID. 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, obtained in May 1996 from a field planted to winter wheat, was 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 before packing. Just before the <4-mm fraction of each soil was packed, its water content was raised slowly 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 almost identical to those reported in Lehrsch et al. (1991). In brief, moistened soil was packed to a dry bulk density of 1.15 Mg m^{-3} by tapping it into brass cylinders 50 mm tall with inside diameters of 28 mm and wall thicknesses of 3 mm. Each packed cylinder was then sealed in a Ziploc[1], polyethylene bag to inhibit water loss and prevent later freeze-drying and placed in 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

[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			COLE[a]	Base sat.	Exch.		Org. C	Initial agg.	Water content	
	Sand	Silt	Clay	(cm cm^{-1})	(%)	Ca	CEC	(g kg^{-1})	stab.[b]	Field-moist	When packed[c]
	(g kg^{-1})					(cmol kg^{-1})			(%)	(kg kg^{-1})	
Barnes loam	440	320	240	0.030	100	–	19.5	16.0	35	0.14	0.22
Sharpsburg silty clay	180	400	420	0.086	94	19.4	29.4	13.3	85	0.12	0.27
Palouse silty clay loam	190	520	290	0.026	82	12.7	19.6	13.2	87	0.13	0.26
Portneuf silt loam	210	560	230	0.012	100	–	12.6	9.9	46	0.14	0.25

[a]Coefficient of linear extensibility.

[b]Measured on the stored soil about 90 days before the experiment was performed.

[c]Equal to the water content at a matric potential of −33kPa.

packed samples were then subjected to either zero, one, two, or four FTCs. The zero-cycle samples were not frozen. The packed soil for the other cycles was frozen convectively, without access to additional water, at −5°C for 48 h and was then thawed at +6°C for 48 h for each freeze-thaw cycle. The freezing chamber was maintained at −5°C (Lehrsch et al. 1992; Rowell and Dillon 1972) to freeze the soil slowly, thereby permitting water redistribution as the soil froze. A data logger with a thermistor scanned the air temperature in the freezing chamber every 5 min and recorded an average once every hour; 95% of these averages were within 0.8°C of the target temperature. After the appropriate samples had been frozen for the last time and had thawed for 48 h, they were brought to room temperature by placing them on a laboratory bench for 2 h. Each sample was then removed from its cylinder and sectioned to obtain samples 0 to 15 and 15 to 30 mm in size. As recommended by Cary (1992), aggregates from shallow (15-mm) layers were analyzed to measure FTC effects on aggregate stability better. The aggregates in each layer were not air-dried but were hand-separated from their neighbors immediately, using slight force between thumb and forefinger. The separated aggregates were sieved gently, again by hand, to obtain moist, 1- to 4-mm aggregates. Four grams of these were then vapor-wetted to 0.30 kg kg^{-1} within 30 min using a nonheating vaporizer (Humidifier No. 240, Hankscraft, Reedsburg, WI). Immediately thereafter, the aggregates were sieved in distilled water for 3 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-dried 1- to 2-mm aggregates, were vapor-wetted before sieving.

Analyses of variance were performed using a mixed model in SAS (SAS Institute Inc. 1989). Soils, FTCs, sampling depths, and their interactions were modeled as fixed effects whereas blocks and the interactions that included blocks were modeled as random effects. An initial Bartlett's test indicated that not all treatment variances were statistically equal. On examination, the variances for Palouse, cycle zero, and depths 0 to 15 and 15 to 30 mm averaged 163, whereas the variances of the remaining 30 treatment combinations averaged 44. Because no transformation was found to equalize such disparate variances, a weighted analysis of variance (ANOVA) was performed, using the reciprocals of these two average variances as weights. When compared with the results from a non-weighted ANOVA, the results from the weighted ANOVA differed little. The residuals from fitting the statistical model using a weighted analysis were normally distributed (Shapiro-Wilk $W = 0.984$, $P = 0.634$). The weighted ANOVA revealed that aggregate stability was affected only by a pair of two-way interactions, one between soils and FTCs ($P = 0.001$) and the other between sampling depths and FTCs ($P = 0.104$). Finally, to aid in the interpretation of the findings, a numerical model of El-Kadi and Cary (1990) was used to simulate soil water redistribution and ice formation because freezing occurred in the cylinders packed with Portneuf silt loam and Palouse silty clay loam, the only soils for which all needed input data were available.

RESULTS AND DISCUSSION

Interaction between Soils and Freeze-Thaw Cycles

Freeze-thaw cycle effects on aggregate stability were soil-dependent. Increasing FTCs increased

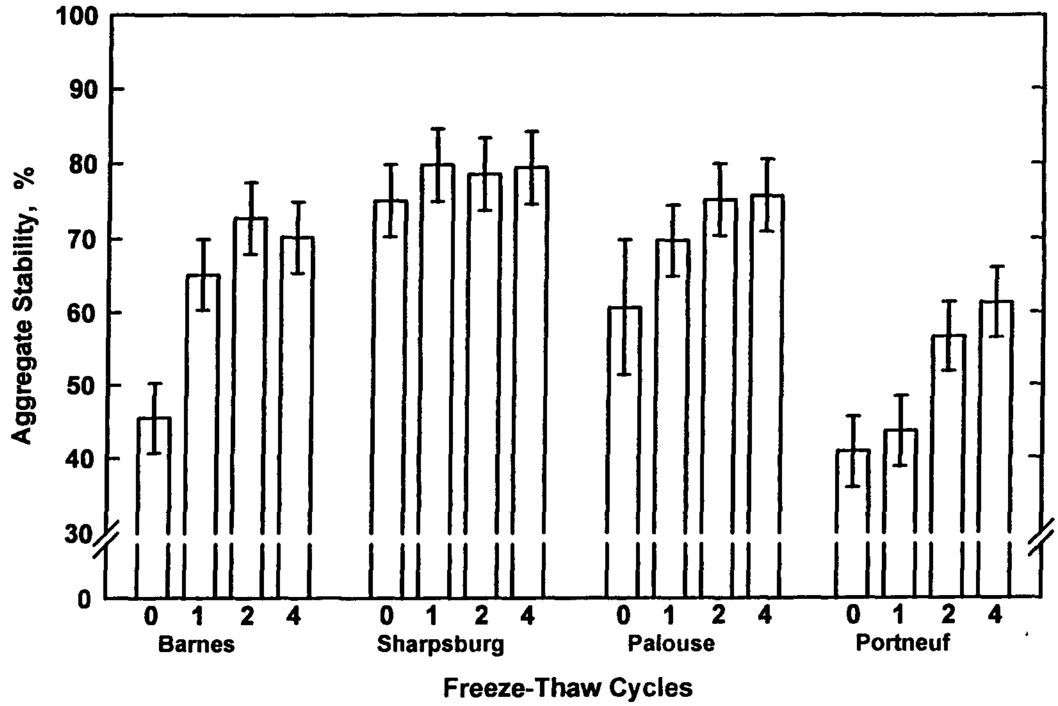

Fig. 1. Aggregate stability of each soil measured at each freeze-thaw cycle, averaged across sampling depths. Each mean ($n = 12$) is shown with its 95% confidence limits.

each soil's aggregate stability when averaged across both sampling depths (Fig. 1). The stability increase from zero to one FTC was significant for Barnes ($P < 0.001$) and Palouse ($P = 0.085$). Perfect et al. (1990) also reported that wet aggregate stability increased after just one FTC. From one to two FTCs, the increase was significant for Barnes ($P = 0.028$) and Portneuf ($P < 0.001$) soils. No other adjacent FTC means within each soil differed at a probability of less than 0.100. The Sharpsburg soil, with 420 g clay kg^{-1}, was the only soil that did not show a significant response from any one FTC level to an adjacent one. However, its aggregate stability stabilized at about 79% from one to four FTCs.

Additional, preplanned, single degree-of-freedom comparisons were made to examine the responses of the Barnes, Palouse, and Portneuf soils more closely. These comparisons confirmed that aggregates that were frozen one or more times, on average, were more stable ($P = 0.01$) than unfrozen aggregates of Barnes and Portneuf soils at both depths and for Palouse aggregates at 0 to 15 mm. Moreover, when surface (0–15 mm) aggregates of either Barnes, Palouse, or Portneuf soils were frozen repeatedly (two or four times), their average stability was greater ($P = 0.01$) than the average stability of surface aggregates that were not frozen or were frozen only once.

This increase in stability of field-moist aggregates with the first one or two 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 interaggregate pores or ice lens enlargement could bring nearby soil particles into contact. Slightly soluble, inorganic bonding agents would then move by mass flow 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 as a result of freezing-induced soil water redistribution (Czurda et al. 1995; Kemper et al. 1987; Perfect et al. 1990). Since this precipitation was probably 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 (Miller 1980) conceivably 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 to improve aggregation and increase aggregate stability (Bisal and Nielsen 1964; Czurda et al. 1995; Perfect et al. 1990; Rowell and Dillon 1972).

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

The data in Fig. 1 suggest that the aggregate stability of the Barnes and Palouse soils, in particular, reached a plateau, or possibly a threshold, from two to four FTCs. To test this tentative finding statistically, an analysis of variance with contrasts was used to test for linear, quadratic, and cubic trends in the response of aggregate stability to increasing FTCs for each soil (Table 2). The analyses confirmed that the aggregate stability of the Barnes and Palouse soils responded in a curvilinear (that is, quadratic) manner to increasing FTCs.

For the most complex trend found to be statistically significant for each soil, a regression equation was fitted to the data. The responses, fitted to data averaged across both depths, were:

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

and

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

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 is greatest just before or at three FTCs. The Portneuf was the only soil of the four we studied whose aggregate stability increased linearly (i.e., the linear trend was significant but the quadratic was not) from zero to four FTCs. Its response was:

TABLE 2

Statistical significance of linear, quadratic, and cubic trends in the effect of freeze-thaw cycles on aggregate stability

	Statistical significance			
	Soil			
Trend	Barnes	Sharpsburg	Palouse	Portneuf
Linear	**[a]	NS[b]	**	**
Quadratic	**	NA[c]	*	NS
Cubic	NS	NA	NS	NA

[a] *, ** Significant at the 0.05 and 0.01 probability levels, respectively.
[b] NS = Not significant.
[c] NA = Not applicable.

$$AS_{Por} = 41.0 + 5.5(FTC) \quad (R^2 = 0.70) \tag{3}$$

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 two or three FTCs. After Sharpsburg aggregates were frozen and thawed at least once, their stability was about 80%, and it did not change significantly 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 both four FTCs (this study) and five FTCs (Lehrsch et al. 1991). The stability of the Portneuf changed little from zero to one FTC. In this experiment, however, its stability from one to two FTCs increased from 43.6 to 56.6% (significant at $P < 0.001$). I have no explanation, other than precipitation of bonding agents at particle contact points during drying (discussed above), for this highly significant 13 percentage point increase.

Interaction between Sampling Depths and Freeze-Thaw Cycles

Freeze-thaw cycle effects on 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 responses, fitted to data that were first averaged across four soils, were:

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

and

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

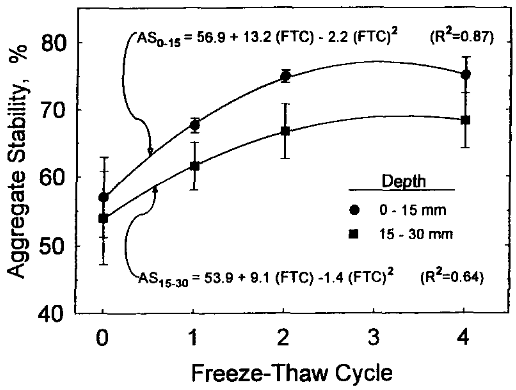

Fig. 2. Freeze-thaw cycle effects on aggregate stability measured at each sampling depth. The responses were fitted to data that were first averaged across four soils. Each mean (n = 6) is shown with its 95% confidence limits.

Equations (4) and (5) also indicate that aggregate stability would be greatest at three or just more than three FTCs at each depth.

At each FTC level, aggregate stability at 0 to 15 mm exceeded that at 15 to 30 mm (Fig. 2). The data also reveal that these differences increased with each cycle through two FTCs. From zero to two FTCs, aggregate stability in the uppermost 15 mm increased by 18 percentage points (about 32%), whereas it increased by 13 percentage points (about 24%) in the second 15 mm. For all soils averaged across all FTCs, aggregate stability at 0 to 15 mm, 68.6%, was nearly 10% greater (significant at $P < 0.001$) than at 15 to 30 mm, 62.6%.

The data in Fig. 2 also reveal that aggregate stability increased more near the surface than below it with each of the first two FTCs. Aggregates near the surface experienced less overburden pressure, i.e., 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 7 percentage points. With such small differences, fall plowing or rototilling that might reduce surface bulk density (i.e., reduce constrainment) 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 to 15- and 15 to 30-mm layers, the rate at which aggregate stability increased with increasing FTCs decreased (Fig. 2). This finding supports the view that slightly soluble bonding agents were being removed from the soil solution by precipitation at intra-aggregate contact points (Kemper et al. 1987; Lehrsch et al. 1991). Most would presumably 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.

Aggregate stability of field-moist aggregates increased with the first two FTCs regardless of depth (Fig. 2). Equations (1), (2), (4), and (5) predict aggregate stability will be greatest near three 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 their surface soil experiences. They could, for example, establish winter cover crops or adopt minimum-till or no-till production systems to greatly increase crop residues on the soil surface. These residues would mulch the surface and trap snow during the winter. Any practice that better insulates the soil should help stabilize surface aggregates. Data in Fig. 2 also show that aggregate stability changed little from two to four FTCs, regardless of depth. With more FTCs, aggregate stability would almost surely decrease (Benoit 1973; Mostaghimi et al. 1988) as the fitted curves in Fig. 2 suggest.

Simulation Modeling

The model ICE-1 (El-Kadi and Cary 1990) was used to simulate soil water movement and ice formation in the Portneuf silt loam and the Palouse silty clay loam. Though these soils differed in their soil water characteristics, saturated hydraulic conductivities, and electrical conductivities, their soil water redistributed similarly as freezing occurred. The model predicted little redistribution until the surface temperature dropped to about −1°C. Then, in response to a thermal gradient, water moved upward from the 20- and 30-mm depths to the 10-mm depth where it froze, possibly forming an ice lens though more likely forming ice crystals in the interaggregate pores. As time passed, water moved from the lower half of the cylinders to the 20-mm depth where freezing also occurred. At depths of 10 and 20 mm, the model predicted that the Portneuf's total water content (liquid plus ice, on a volume basis) reached a maximum of about 0.41 $m^3\ m^{-3}$ after 48 h. At those depths, its liquid water content, in contrast, was only 0.16 $m^3\ m^{-3}$, approaching that at the permanent wilting point. At these very low liquid water contents and relatively low temperatures, precipitation of bonding agents was likely. At 30 mm and below, the Portneuf's liquid water content was predicted to be about 0.21 $m^3\ m^{-3}$, nearly 28% less than its initial value of 0.29 $m^3\ m^{-3}$. Because the Palouse's water content (when packed) was greater than the Portneuf's (Table 1), its total water content near its freezing front at 10 to 20 mm was greater than the Portneuf's, 0.47 versus 0.41 $m^3\ m^{-3}$. Although the Palouse had a greater total water content than the Portneuf at 10 to 20 mm, it had a smaller liquid water content, 0.13 versus 0.16 $m^3\ m^{-3}$. This greater drying could explain, in part, the greater aggregate stability of the Palouse compared with the Portneuf at all FTC levels (Fig. 1).

Although the ICE-1 model (El-Kadi and Cary 1990) provided valuable insight into the redistribution patterns, it also predicted that after 48 h in the freezing chamber, only liquid water would be present in the soil at and below the 30-mm depth. Preliminary tests indicated that the packed soil in this experiment was frozen throughout after 48 h. Heat conduction through the soil to the cylinder wall, then upward through the brass to the colder air above, may explain why the soil in the cylinders was frozen. In these frozen samples, neither ice lenses nor frost heaving were observed. Some ice crystals were seen, however, on the soil surfaces. Freezing did cause some slight upward water movement in the Portneuf samples, but little was detected in the Palouse samples.

Soil structure will deteriorate where soils at high water contents (those higher than field capacity) are frozen, particularly in regions where their total water content exceeds their total pore space, i.e., where soil heaving occurs (Cary 1987; Edwards 1991; Lehrsch et al. 1991). Results reported here and earlier (Lehrsch et al. 1991, 1993) suggest that structure can initially be improved (i.e., stability increased) in soils with lower water contents where drying occurs in a soil region as liquid water flows from it to freeze elsewhere.

Additional studies should be conducted to identify the physical and/or chemical constituents that may be (i) be 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 should add a sodium silicate and/or 2 g kg^{-1} $CaSO_4$ treatment (Lehrsch et al. 1993). Cylinders of a material less conductive than brass would better simulate field conditions. 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, in particular to compare soils with quite different (high and low) organic C contents.

CONCLUSIONS

The stability of wet-sieved, field-moist aggregates of Barnes, Palouse, and Portneuf soils increased with one and/or two FTCs. From two to four FTCs, little additional change occurred. The stability of Sharpsburg silty clay aggregates was not affected significantly by FTCs. Trend analysis revealed that aggregate stability would be greatest, in general, after two or three FTCs. When averaged across four soils, FTCs stabilized aggregates more at 0 to 15 than 15 to 30 mm. In the uppermost 30 mm of wet soils, two or three FTCs may increase rather than decrease aggregate stability.

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