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Water infiltration and soil structure related to organic matter and its stratification with depth

A.J. Franzluebbers*

USDA Agricultural Research Service, J. Phil Campbell Sr. Natural Resources Conservation Center, 1420 Experiment Station Road, Watkinsville, GA 30677-2373, USA

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Abstract

Soil organic matter is a key attribute of soil quality that impacts soil aggregation and water infiltration. Two soils (Typic Kanhapludults), one under long-term management of conventional tillage (CT) and one under long-term management of no tillage (NT), were sampled to a depth of 12 cm. Soil cores (15 cm diameter) were either left intact or sieved and repacked to differentiate between short-term (sieving) and long-term (tillage management) effects of soil disturbance on water infiltration, penetration resistance, soil bulk density, macroaggregate stability, and soil organic carbon (SOC). Mean weekly water infiltration was not different between sieved and intact cores from long-term CT (22 cm h^{-1}), but was significantly greater in intact (72 cm h^{-1}) than in sieved (28 cm h^{-1}) soil from long-term NT. The stratification ratio of SOC (i.e., of 0–3 cm depth divided by that of 6–12 cm depth) was predictive of water infiltration rate, irrespective of short- or long-term history of disturbance. Although tillage is used to increase soil porosity, it is a short-term solution that has negative consequences on surface soil structural stability, surface residue accumulation, and surface-SOC, which are critical features that control water infiltration and subsequent water transmission and storage in soil. The stratification ratio of SOC could be used as a simple diagnostic tool to identify land management strategies that improve soil water properties (e.g., infiltration, water-holding capacity, and plant-available water). Published by Elsevier Science B.V.

Keywords: Bulk density; Conservation tillage; Macroaggregation; Mean-weight diameter; Soil organic carbon; Soil quality

1. Introduction

Soil organic matter sustains many key soil functions by providing the energy, substrates, and biological diversity to support biological activity, which affects soil aggregation and water infiltration. Aggregation is important in: (i) facilitating water infiltration; (ii) providing adequate habitat space for soil organisms; (iii) adequate oxygen supply to roots and soil organisms; and (iv) preventing soil erosion. Infiltration is an important soil feature that controls leaching, runoff, and crop water availability.

Lack of residue cover and exposure of soil to high-intensity rainfall results in poor aggregation, crusting, reduced plant-water availability, erosion, and off-site impacts of sedimentation and poor water quality. Conservation tillage management with surface residue accumulation has been shown to reduce soil erosion by buffering the soil surface against rainfall impact (Langdale et al., 1992).

The degree of soil organic matter stratification with depth has been suggested as an indicator of "soil quality", because surface organic matter is essential

* Tel.: +1-706-769-5631; fax: +1-706-769-8962.
E-mail address: afranz@arches.uga.edu (A.J. Franzluebbers).

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to erosion control, water infiltration, and conservation of nutrients (Franzluebbers, 2002). My objective was to build upon this hypothesis by developing quantitative relationships between the stratification ratio of SOC and water infiltration, soil aggregation, and soil porosity. To be able to distinguish the short-term from the long-term effect of soil disturbance, two similar soils with different long-term tillage management histories (i.e., long-term disturbance regimes) were subjected to both undisturbed and disturbed conditions (i.e., sieving).

2. Materials and methods

2.1. Soils

Two sites under ~25 years of continuous management were located on opposite sides of a road near Watkinsville, GA (33°62′N latitude; 83°25′W longitude). Management systems were: (1) long-term conventional tillage (CT) with winter small grains (i.e., wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and rye (*Secale cereale* L.)) and (2) long-term no tillage (NT) with summer/winter double cropping (i.e., sorghum (*Sorghum bicolor* (L.) Moench), cotton (*Gossypium hirsutum* L.), soybean (*Glycine max* (L.) Merr.), wheat, rye, barley, and crimson clover (*Trifolium incarnatum* L.)). Soil under CT had not been tilled for ~14 months prior to sampling, which resulted in a consolidated soil that was free from immediate disturbance. CT was with a tandem disk 2–3 times per year to a depth of 10–15 cm. Soils were Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults). Long-term mean annual air temperature is 16.5 °C, precipitation is 1250 mm, and pan water evaporation is 1560 mm. Mean elevation is 230 m.

2.2. Experimental setup

Twenty-four soil cores (15 cm diameter, 12 cm deep) were collected within each long-term management system from an area of ~3 m^2 on 7 January 2000. Polyvinyl chloride pipe (15 cm long) was pushed gently into the soil with a hydraulic probe. Half of the soil cores from both long-term management systems were sieved (<8 mm), mixed, and loosely settled into cores to create a uniform distribution of organic matter that simulated tillage. The other half of soil cores were kept intact.

The experimental design was a randomized, complete block design with three replicates of four treatments, which were repeated four times to accommodate destructive sampling at 2, 6, and 13 weeks, and an additional harvest at 13 weeks from soil cores planted to wheat at 6 weeks. Wheat was planted to meet a separate objective not addressed in this report for estimating plant-available nutrient supply.

Soils were incubated in a glasshouse without temperature control for up to 13 weeks from 11 January to 11 April 2000. Deionized water was applied to each soil core on a weekly basis at a rate of 2.8 cm (500 cm^3) within a 10 s period through a platform (1.6 mm diameter holes on 1 cm grid) elevated 1 m above the soil cores. The irrigation design allowed: (1) a standardized approach throughout the study; (2) sufficient energy to disrupt the soil surface and simulate heavy rainfall contributing to surface soil crusting; and (3) sufficient ponding of water to estimate infiltration rate. The time required for all water to enter the soil surface was recorded and this value was converted to infiltration rate based on the quantity of water and surface area of soil:

$$\text{Infiltration}\,(\text{cm}\,\text{h}^{-1}) = \frac{Q}{A \times T}$$

where Q is the quantity of water (500 cm^3), A the area (176.7 cm^2), and T the time (h) (Bouwer, 1986). At 1 week, the quantity of water was only 200 cm^3. Between 11 and 12 weeks of incubation, an extra application of 250 cm^3 of water was made to avoid plant desiccation. Leachate quantity was measured the morning following irrigation (~20 h) and reflected differences in water-holding capacity and quantity of water lost to evaporation (and transpiration of plants when present) among treatments.

At 2, 6, and 13 weeks of incubation immediately prior to scheduled irrigation, three replicates of each treatment (i.e., CT-intact, CT-sieved, NT-intact, and NT-sieved) were removed from the glasshouse. Soil penetration resistance was determined at three locations within each core with a cone penetrometer (30° tip) inserted to a depth of 2.5 cm (Bradford, 1986). Soil from depths of 0–1, 1–3, 3–6, and 6–12 cm was removed from each cylinder by slicing soil above the cylinder following placement of spacers underneath to accurately determine depth. Soil was weighed before and after drying at 55 °C for 3 days. Soil was gently crushed to pass a 4.75 mm screen prior to further analyses.

At 6 weeks of incubation and 1 day following the scheduled irrigation, half of the remaining soil cores were planted with 14 pregerminated wheat (cv. Georgia Gore) seeds on an evenly spaced grid.

2.3. Soil analyses

Soil bulk density was determined at depths of 0–1, 1–3, 3–6, and 6–12 cm at 2, 6, and 13 weeks by calculating mass per unit volume. Soil porosity was calculated as the fraction of total volume not occupied by soil assuming a particle density of 2.65 Mg m^{-3} (Danielson and Sutherland, 1986). Water-filled pore space was calculated as the volumetric water content divided by total porosity.

Subsamples of soil were ground in a ball mill for 5 min and analyzed for total C and N using dry combustion at 1350 °C (Leco CNS-2000, St. Joseph, MI).[1]

Dry-stable aggregate distribution was determined by placing a 100 g portion of soil (50 g portion for 0–1 cm depth) on top of a nest of sieves (20 cm diameter), shaking for 1 min at Level 6 on a scale of 0–10 on a vibrating CSC Scientific Sieve Shaker (Catalogue no. 18480, CSC Scientific, Fairfax, VA), and weighing soil retained on the 1.0, 0.25, and 0.053 mm screens and that passing the 0.053 mm screen.

Water-stable aggregate distribution was determined by placing the same soil sample used for dry-stable aggregate distribution on top of a nest of sieves (17.5 cm diameter with openings of 1.0 and 0.25 mm), immersing directly in water, and oscillating for 10 min (20 mm stroke length, 31 cycles min^{-1}). After removing the two sieves and placing them in an oven to dry, water containing soil passing the 0.25 mm screen was poured over a 0.053 mm screen, the soil was washed with a gentle stream of water, and the soil retained transferred into a drying bottle with a small stream of water. The <0.053 mm fraction was calculated as the difference between initial soil weight and summation of the other fractions. All fractions were oven dried at 55 °C for ≥24 h following visual dryness.

Mean-weight diameter of both dry- and water-stable aggregates was calculated by summing the products of aggregate fraction weight and mean diameter of aggregate classes (Kemper and Rosenau, 1986). Stability of mean-weight diameter was calculated as water-stable mean-weight diameter divided by dry-stable mean-weight diameter. Macroaggregates were defined as the fraction >0.25 mm. Stability of macroaggregates was calculated as the weight of water-stable macroaggregates divided by the weight of dry-stable macroaggregates.

Stratification ratio of soil properties was calculated as the concentration at 0–3 cm divided by the concentration at 6–12 cm. (Note: the properties at 0–3 cm depth considered bulk density at depth increments of 0–1 and 1–3 cm.)

2.4. Statistical analyses

Infiltration rate and penetration resistance were log transformed prior to statistical analysis. Infiltration rate, penetration resistance, and soil properties within each depth were analyzed for variance separately within each measurement period using the general linear models procedure of SAS Institute (1990). Soil properties were also pooled across measurement periods, since few differences occurred among measurement periods and were not expected during the short incubation period. Differences among treatments were considered significant at $P \leq 0.05$. Linear and non-linear regressions were used to test relationships among variables using SigmaPlot 5.0 (SPSS, 1998).

3. Results and discussion

3.1. Depth distribution of soil properties

Soil organic C was highly stratified with soil depth under long-term NT and relatively uniformly distributed with soil depth under long-term CT (Fig. 1). Soil organic C concentration was significantly greater under long-term NT than under long-term CT in the upper 6 cm of soil. To a depth of 12 cm, the standing stock of SOC was half the amount under CT as under NT (0.94 vs. 1.89 kg m^{-2}). Although long-term tillage

[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the US Department of Agriculture.

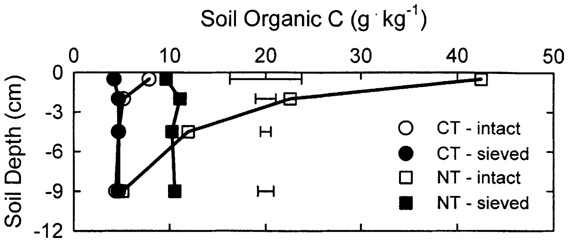

Fig. 1. Soil organic C depth distribution in response to short-term (intact vs. sieved) and long-term (CT vs. NT) soil disturbance regimes. Error bars are LSD among treatments within a soil depth at $P = 0.05$.

management may have been the major reason for this result, management also differed in cropping intensity and fertilization history. The focus of this paper is not the absolute change in SOC, but attainment of soil differences that are typical of long-term tillage management. Greater SOC content in surface soil under long-term NT compared with CT is consistent with previous results (Reicosky et al., 1995).

Sieving of soil resulted in a uniform distribution of SOC in soils taken from under long-term CT and NT (Fig. 1). Sieved soil under long-term NT contained approximately double the concentration of SOC as that of sieved soil under long-term CT throughout the 12 cm of soil. Sieving reduced soil bulk density in both soils, but only significantly at a depth of 6–12 cm in the soil from under long-term CT and at a depth of 3–12 cm in the soil from under long-term NT (Fig. 2). Sieving increased soil bulk density in the soil from under long-term NT at a depth of 0–3 cm because the high concentration of SOC at the soil surface was replaced with a soil mixture with lower concentration of organic C. Soil organic C has a direct impact on the

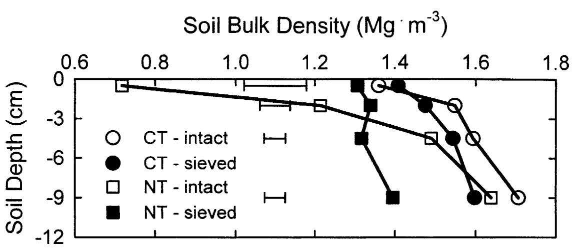

Fig. 2. Soil bulk density depth distribution in response to short-term (intact vs. sieved) and long-term (CT vs. NT) soil disturbance regimes. Error bars are LSD among treatments within a soil depth at $P = 0.05$.

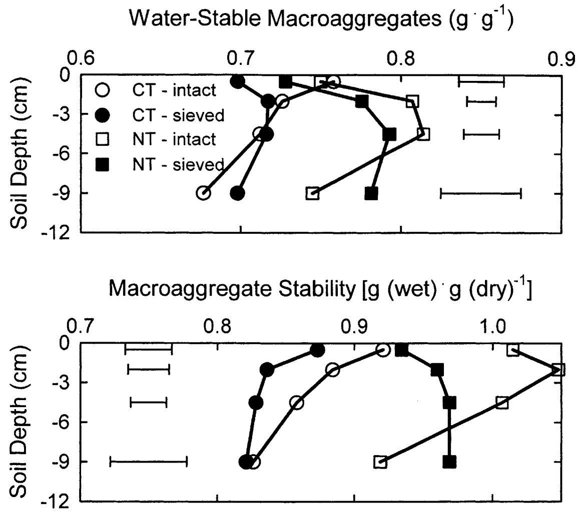

Fig. 3. Water-stable macroaggregates and stability in response to short-term (intact vs. sieved) and long-term (CT vs. NT) soil disturbance regimes. Error bars are LSD among treatments within a soil depth at $P = 0.05$.

bulk density (or inversely on the porosity) of soil, since the particle density of organic matter is considerably lower than that of mineral soil and soil organic matter is often associated with increased aggregation and permanent pore development as a result of soil biological activity (Pikul and Zuzel, 1994; Franzluebbers et al., 2000).

Water-stable macroaggregation (Fig. 3) and mean-weight diameter of water-stable aggregates (Fig. 4) did not vary greatly among tillage systems, disturbance treatments, or soil depth. In general, soil under long-term NT contained a greater fraction of macroaggregates than under long-term CT (Fig. 3). Sieving of soils had few significant effects on water-stable macroaggregation or on mean-weight diameter of water-stable aggregates. The procedure for determining water-stable macroaggregates and mean-weight diameter of water-stable aggregates did not differentiate between true aggregates and large sand particles that were retained on screens. Therefore, the stability of macroaggregates and the stability of mean-weight diameter (i.e., wet divided by dry) are considered more reflective of dynamic soil properties influenced by management.

Macroaggregate stability and mean-weight diameter stability were greater under long-term NT than under long-term CT at all soil depths (Figs. 3 and 4).

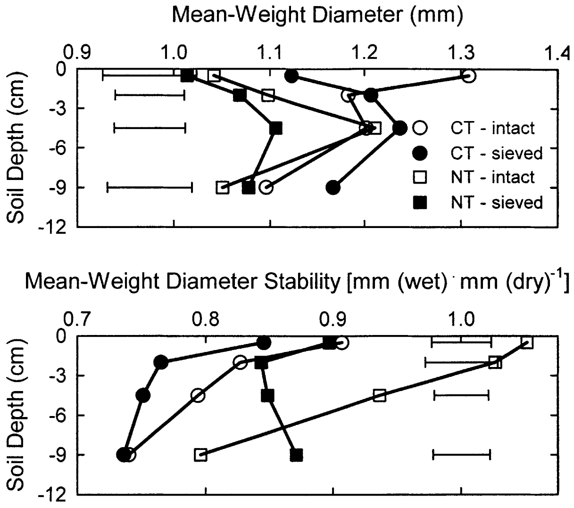

Fig. 4. Water-stable mean-weight diameter and stability in response to short-term (intact vs. sieved) and long-term (CT vs. NT) soil disturbance regimes. Error bars are LSD among treatments within a soil depth at $P = 0.05$.

Further, sieving caused a shift towards more uniform depth distribution of these soil properties than when soil was intact. Both short-term and long-term effects of soil disturbance on aggregate stability indices were consistent with the homogenization of SOC distribution with depth and consistent with previous results on similar soils (Bruce and Langdale, 1997).

3.2. Stratification ratio of SOC in relationship with soil water characteristics

The ratio of SOC at a depth of 0–3 cm to that at 6–12 cm averaged 1.4 under long-term CT and 5.3 under long-term NT. Sieving reduced these ratios to 1.0 for both soils. Stratification ratio of SOC would have been greater for both intact soils if the 0–1 cm depth alone would have been compared to the lower depth, but this thin soil layer would not be practically isolated because of the uncertainty associated with obtaining an accurate depth of sampling.

Infiltration of water into intact soils was always greater under long-term NT than under long-term CT, except at Week 12 in which no statistical difference occurred (Table 1). On average, infiltration rate was more than three times greater under long-term NT than under long-term CT. This difference in infiltration rate was also strongly related to the difference in stratification ratio of SOC (Fig. 5). During Weeks 0 and 1, infiltration rate was non-linearly related to stratification ratios of SOC, such that a plateau was reached at ratios >5. In contrast, a linear relationship between infiltration rate and stratification of SOC occurred during Weeks 7–12. Greater water infiltration under NT compared with CT has been frequently reported when tillage systems have been in place for many years (Dao, 1993; Bruce and Langdale, 1997; Gilley et al., 1997; Arshad et al., 1999), however, with management for less than a few years, water infiltration under NT may be similar or lower than under CT due to initial compaction and lack of sufficient biological activity for development of stable soil structure (Lindstrom and Onstad, 1984; Unger, 1992).

Sieving of soil under long-term CT resulted in inconsistent effects on infiltration rate during the course of the 13-week incubation (Table 1). Infiltration rate was greater with intact compared with sieved soil on seven occasions, but was lower with intact compared with sieved soil on five occasions. On average, sieving of soil under long-term CT had no effect on infiltration rate. The short-term disturbance of sieving appeared to be a mere continuation of soil

Table 1
Water infiltration rate in response to short-term (intact vs. sieved) and long-term (CT vs. NT) soil disturbance regimes during the course of a 12-week greenhouse incubation[a]

Week	Long-term CT		Long-term NT		$LSD_{(P=0.05)}$
	Intact	Sieved	Intact	Sieved	
Infiltration (cm h^{-1})					
0	67	9	239	25	1
1	36	25	78	19	2
2	4	47	37	18	2
3	6	61	27	28	2
4	22	19	44	33	2
5	21	19	31	32	2
6	20	11	33	19	2
7	17	16	67	30	2
8	19	19	110	44	2
9	15	17	90	38	1
10	10	13	76	37	1
11	11	13	74	32	2
12	37	13	32	8	6
Mean	22 b	22 b	72 a	28 b	

[a] Infiltration rate was calculated as the time required for ponded water to enter the soil surface. Quantity of water was 2.8 cm for each event, except at Week 1, which was 1.1 cm.

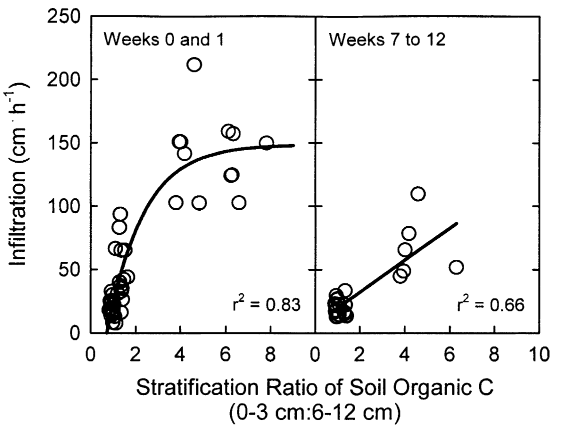

Fig. 5. Relationship between stratification ratio of SOC and infiltration rate during early and late periods of the glasshouse incubation.

rearrangement that had been occurring throughout the long term.

Sieving of soil under long-term NT resulted in significantly reduced infiltration rate on 11 of the 13 occasions, and on average, reduced infiltration rate to 39% of that observed in intact soil (Table 1). On average, infiltration rate of sieved soil under long-term NT was not significantly different from that under intact or sieved soil under long-term CT. However, from Week 4 until Week 11, infiltration rate of sieved soil under long-term NT was double that of sieved soil under long-term CT. During the first 3 weeks of incubation, reconsolidation of sieved soil may have been a factor that caused inconsistent effects contrary to those observed later. Although double the amount of SOC (NT-sieved vs. CT-sieved) tended to improve water infiltration rate, these results clearly indicate that location (i.e., stratification with soil depth) of SOC is more important to the rate of water infiltration than total quantity of SOC. Incorporation of various organic amendments to a soil in California during 2 years increased SOC content 48 ± 31% and improved water infiltration by 40 ± 15% due to stimulation of soil microbial activity and development of more stable aggregates (Martens and Frankenberger, 1992).

Greater SOC stratification with long-term NT compared with long-term CT led to greater gravimetric soil water content in the 0–3 cm depth at all sampling periods (Table 2). This occurred when evaporative demand was low early in the incubation, as well as

Table 2

Soil water content, water-filled pore space, and penetration resistance at 2, 6, and 13 weeks of incubation in response to short-term (i.e., intact vs. sieved) and long-term (i.e., CT vs. NT) soil disturbance regimes

Week	Long-term CT		Long-term NT		$LSD_{(P=0.05)}$
	Intact	Sieved	Intact	Sieved	
Soil water content of 0–3 *cm* ($g\ g^{-1}$)					
2	0.11	0.09	0.26	0.15	0.04
6	0.02	0.01	0.15	0.06	0.02
13	0.02	0.03	0.05	0.04	0.01
13 (planted)	0.01	0.01	0.03	0.01	0.01
Mean	0.04	0.04	0.12	0.07	0.03
Water-filled pore space of 0–3 *cm* ($m^3\ m^{-3}$)					
2	0.39	0.26	0.43	0.36	0.08
6	0.07	0.06	0.30	0.19	0.04
13	0.08	0.10	0.10	0.12	0.03
13 (planted)	0.04	0.04	0.05	0.03	0.03
Mean	0.15	0.12	0.22	0.17	0.05
Penetration resistance (*kPa*)					
2	18	2	3	3	41
6	97	60	10	2	2
13	287	166	22	32	2
13 (planted)	257	277	30	103	2
Mean	106	47	12	13	3

when evaporative demand was high later in the incubation. Soil organic matter has a greater water-holding capacity than mineral soil, and this effect was reflected in the soil water content. However, due to the low density of soil organic matter, water content expressed on a volumetric basis (i.e., water-filled pore space) was not always significantly different at individual sampling periods, but was still greater under long-term NT compared with long-term CT averaged across sampling periods.

Sieving compared with intact soil under long-term NT reduced gravimetric soil water content and water-filled pore space in the 0–3 cm depth (Table 2). This result was likely due to differences in SOC and its affinity for water. Due to the lack of stratification of SOC under long-term CT, sieving had few significant effects on soil water content and water-filled pore space compared with intact soil.

The portion of water leached from intact soil cores following irrigation was consistently lower under long-term NT than under long-term CT (Table 3).

Table 3
Portion of water leached from soil cores in response to short-term (i.e., intact vs. sieved) and long-term (i.e., CT vs. NT) soil disturbance regimes during the course of a 13-week greenhouse incubation[a]

Week	Long-term CT		Long-term NT		$LSD_{(P=0.05)}$
	Intact	Sieved	Intact	Sieved	
Portion of water leached (ml ml^{-1})					
0	0.36	0.13	0.18	0.01	0.06
1	0.34	0.06	0.17	0.11	0.06
2	0.65	0.46	0.54	0.36	0.08
3	0.66	0.54	0.60	0.50	0.04
4	0.47	0.43	0.37	0.29	0.04
5	0.50	0.44	0.46	0.36	0.04
6	0.46	0.41	0.40	0.31	0.05
7	0.34 (0.35)	0.29 (0.29)	0.29 (0.30)	0.17 (0.17)	0.06
8	0.31 (0.30)	0.25 (0.20)	0.24 (0.22)	0.14 (0.08)	0.06
9	0.29 (0.29)	0.23 (0.15)	0.22 (0.21)	0.13 (0.05)	0.04
10	0.35 (0.33)	0.34 (0.19)	0.27 (0.24)	0.18 (0.08)	0.04
11	0.34 (0.33)	0.30 (0.14)	0.26 (0.20)	0.16 (0.03)	0.05
12	0.30 (0.28)	0.28 (0.20)	0.23 (0.22)	0.24 (0.14)	0.05
Mean	0.41 a	0.32 b	0.33 b	0.23 c	

[a] Values in parentheses beginning at 7 weeks are from cores planted to wheat 1 day following irrigation at 6 weeks. Note: irrigation amounts were 2.8 cm for all dates, except 1.1 cm at Week 1 and an extra irrigation of 2.8 cm midway between Weeks 11 and 12.

This difference suggests greater water-holding capacity of the 0–12 cm depth under long-term NT than under long-term CT. Total porosity was greater under long-term NT (0.45 $m^3 m^{-3}$) than under long-term CT (0.39 $m^3 m^{-3}$) as a result of differences in soil bulk density (Fig. 2). More pore space could lead to greater water retention, although the arrangement of pores also has an effect on water retention. It is possible that a part of the difference in the amount of water leached was due to greater evaporation of the wetter soil surface under NT than under CT, although available literature from field experiments does not support this (Lascano et al., 1994).

Sieving reduced the portion of water leached from soil cores under both long-term CT and NT (Table 3). This would be expected, since sieving (as a simulation of tillage) reduced soil bulk density and increased total porosity. Greatest differences between intact and sieved soils occurred during the first 3 weeks until reconsolidation of soil occurred. Total porosity was 0.49 $m^3 m^{-3}$ under sieved soil from long-term NT (8% increase compared with intact soil) and 0.42 $m^3 m^{-3}$ under sieved soil from long-term CT (7% increase compared with intact soil).

3.3. Stratification ratio of SOC in relationship with soil structural properties

The stability of mean-weight diameter and the stability of macroaggregates from a depth of 0–3 cm were non-linearly related to the stratification of SOC (Fig. 6). These relationships suggest that soil surface aggregation is highly dependent upon surface residue management, namely the accumulation of residues without incorporation. The soil surface is viewed as a critical zone that can either impede (e.g., soil crusting) or facilitate (e.g., excellent soil structure with water-stable aggregates) the movement of water into soil. Stable surface soil structure is important for facilitating rapid water infiltration, controlling soil erosion, and reducing water runoff of soil contaminants to nearby surface waters. Stability of mean-weight diameter of soil aggregates from a depth of 0–3 cm was linearly related with infiltration rate during Weeks 0 and 1 ($r^2 = 0.61$) and during Weeks 7–12 ($r^2 = 0.71$).

Total soil porosity at a depth of 0–3 cm was non-linearly related to the stratification of SOC (Fig. 7). In combination with a stable soil structure at the soil

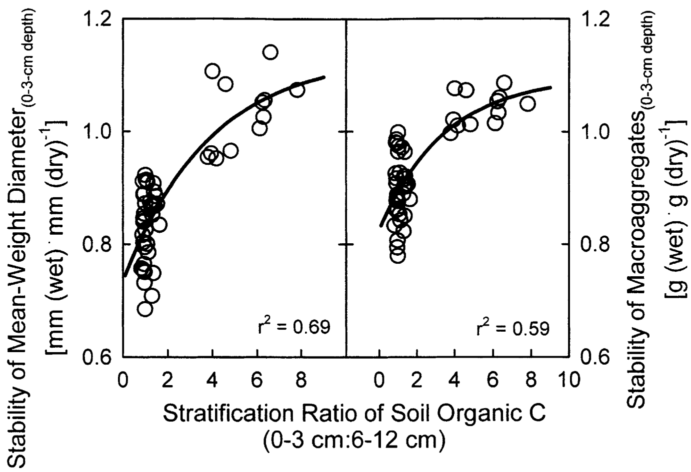

Fig. 6. Relationship between stratification ratio of SOC and stability of mean-weight diameter and macroaggregates at a depth of 0–3 cm.

surface, soil porosity facilitates storage and transmission of water in soil. As expected, the stratification ratio of soil bulk density (i.e., 0–3 cm depth divided by 6–12 cm depth) was strongly negatively related to infiltration rate during Weeks 0 and 1 ($r^2 = 0.80$) and during Weeks 7–12 ($r^2 = 0.64$).

The stratification ratios of either total soil porosity or soil bulk density might be more mechanistically related to the soil function of water infiltration than the stratification ratio of SOC, but detecting significant and consistent changes in soil bulk density due to management is considered less likely than for SOC. Soil organic C and soil bulk density are often highly related (Fig. 8), such that an empirical approach to determine soil functioning with the stratification of SOC becomes reasonable.

Penetration resistance of intact soil was always less under long-term NT with a high stratification ratio of SOC than under long-term CT with a low stratification ratio of SOC (Table 2). As soil became drier later in the study, the difference in penetration resistance between long-term tillage systems increased. Sieving reduced penetration resistance initially in both soils, but upon reconsolidation and development of surface crusting with repeated exposure to high-intensity rainfall, penetration resistance became greater when sieved than left intact.

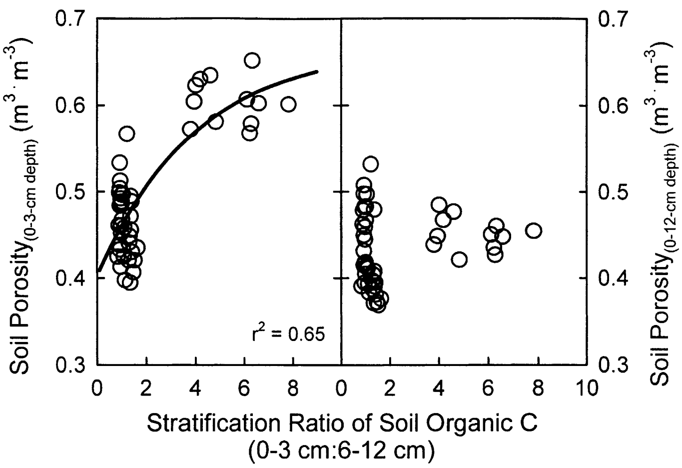

Fig. 7. Relationship between stratification ratio of SOC and soil porosity at 0–3 and at 0–12 cm.

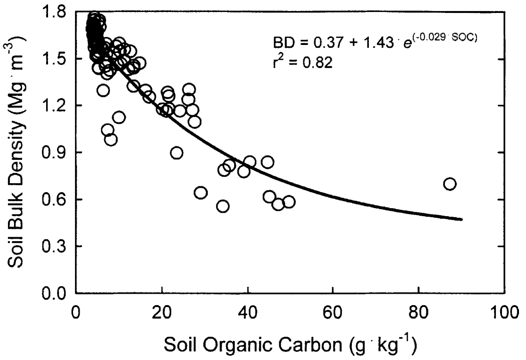

Fig. 8. Relationship between SOC and soil bulk density at depths of 0–1, 1–3, 3–6, and 6–12 cm from intact soil under long-term CT and NT.

4. Summary and conclusions

Short-term soil disturbance (i.e., sieving as a simulation of tillage) of previously stratified soil led to uniform distribution of SOC, reduced soil bulk density, and increased water retention, at least initially. Greater total SOC content (i.e., sieved NT vs. sieved CT) reduced soil bulk density by 12% and improved water infiltration by 27%. Greater stratification of SOC content (i.e., long-term intact NT vs. intact CT) reduced soil bulk density by 10% and improved water infiltration nearly threefold. This greenhouse experiment suggests that stratification ratio of SOC could be used as a simple diagnostic tool to identify land management strategies that restore critical soil functions, such as water infiltration. Detailed field studies under a wide range of conditions will need to be investigated to support these findings.

Acknowledgements

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References

Arshad, M.A., Franzluebbers, A.J., Azooz, R.H., 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada. Soil Till. Res. 53, 41–47.

Bouwer, H., 1986. Intake rate: cylinder infiltrometer. In: Klute, A. (Ed.), Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. Agronomy Monograph No. 9. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 825–844.

Bradford, J.M., 1986. Penetrability. In: Klute, A. (Ed.), Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. Agronomy Monograph No. 9. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 463–478.

Bruce, R.R., Langdale, G.W., 1997. Soil carbon level dependence upon crop culture variables in a thermic–udic region. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America. CRC Press, Boca Raton, FL, pp. 247–261.

Danielson, R.E., Sutherland, P.L., 1986. Porosity. In: Klute, A. (Ed.), Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. Agronomy Monograph No. 9. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 443–461.

Dao, T.H., 1993. Tillage and winter wheat residue management effects on water infiltration and storage. Soil Sci. Soc. Am. J. 57, 1586–1595.

Franzluebbers, A.J., 2002. Soil organic matter stratification ratio as an indicator of soil quality. Soil Till. Res. 66, 95–106.

Franzluebbers, A.J., Stuedemann, J.A., Schomberg, H.H., Wilkinson, S.R., 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32, 469–478.

Gilley, J.E., Doran, J.W., Karlen, D.L., Kaspar, T.C., 1997. Runoff, erosion, and soil quality characteristics of a former Conservation Reserve Program site. J. Soil Water Conserv. 52, 189–193.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis. Part I. Physical and Mineralogical Methods. Agronomy Monograph No. 9. American Society of Agronomy, Soil Science Society of America, Madison, WI, pp. 425–442.

Langdale, G.W., West, L.T., Bruce, R.R., Miller, W.P., Thomas, A.W., 1992. Restoration of eroded soil with conservation tillage. Soil Technol. 5, 81–90.

Lascano, R.J., Baumhardt, R.L., Hicks, S.K., Heilman, J.L., 1994. Soil and plant water evaporation from strip-tilled cotton: measurement and validation. Agron. J. 86, 987–994.

Lindstrom, M.J., Onstad, C.A., 1984. Influence of tillage systems on soil physical parameters and infiltration after planting. J. Soil Water Conserv. 39, 149–152.

Martens, D.A., Frankenberger Jr., W.T., 1992. Modification of infiltration rates in an organic-amended irrigated soil. Agon. J. 84, 707–717.

Pikul Jr., J.L., Zuzel, J.F., 1994. Soil crusting and water infiltration affected by long-term tillage and residue management. Soil Sci. Soc. Am. J. 58, 1524–1530.

Reicosky, D.C., Kemper, W.D., Langdale, G.W., Douglas Jr., C.L., Rasmussen, P.E., 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50, 253–262.

SAS Institute, 1990. SAS User's Guide: Statistics, Version 6th Edition. SAS Institute, Inc., Cary, NC.

SPSS, 1998. SigmaPlot 5.0 Programming Guide. Chicago, IL.

Unger, P.W., 1992. Infiltration of simulated rainfall: tillage system and crop residue effects. Soil Sci. Soc. Am. J. 56, 283–289.