Organic Carbon Influences on Soil Particle Density and Rheological Properties

Humberto Blanco-Canqui,* R. Lal, W. M. Post, R. C. Izaurralde, and M. J. Shipitalo

ABSTRACT

Soil particle density (ρ_s) is not routinely measured and is assumed to range between 2.60 and 2.70 Mg m^{-3} or to be a constant (2.65 Mg m^{-3}) when estimating essential properties such as porosity, and volumetric water and air relations. Values of ρ_s for the same soil may, however, differ significantly from the standard range due to management-induced changes in soil organic carbon (SOC) concentrations. We quantified the ρ_s and Atterberg limits of a Rayne silt loam for five long-term (>22 yr) moldboard-plowed continuous corn (*Zea mays* L.; MP), no-till continuous corn (NT), no-till continuous corn with beef cattle manure (NTm), pasture, and forest systems. We also assessed the relationships of SOC concentration with ρ_s and the Atterberg limits and the impact of ρ_s on soil porosity. Mean ρ_s across NT, NTm, and pasture (2.35 Mg m^{-3}) was ~7% lower than that for MP in the 0- to 10-cm soil depth (2.52 Mg m^{-3}, $P < 0.01$). Forest had the lowest ρ_s of all soils (1.79 Mg m^{-3}). The NTm caused a greater reduction in ρ_s and a greater increase in SOC concentration, liquid limit (LL), plastic limit (PL), and plasticity index (PI) than NT. Surface soils under MP had the highest ρ_s and ρ_b and the lowest SOC concentration, LL, PL, and PI. The SOC concentration was correlated negatively with ρ_s ($r^2 = 0.75$) and positively with Atterberg limits ($r^2 > 0.64$) at >20-cm depth. Estimates of soil porosity for NT, NTm, and pasture using the constant ρ_s overestimated the "true" porosity by 12% relative to that using the measured ρ_s.

A RELIABLE MEASURE of ρ_s, the mass per unit volume of the inorganic and organic soil solids, is required to calculate total porosity, rates of particle sedimentation, heat capacity, thermal conductivity, and water and air relations on a volumetric basis (Hillel, 1998). These ρ_s-based parameters are essential to understanding and modeling several processes including water, air, and heat flow as well as chemical transport through the soil. Such numerous and important applications of ρ_s necessitate an accurate measurement of this soil physical property. The ρ_s is not, however, routinely measured during soil characterization because it is often assumed to range between 2.60 and 2.70 Mg m^{-3} or equal a constant value of 2.65 Mg m^{-3} for most quartz-dominated soils (Hillel, 1998). Thus, derivation of soil properties requiring ρ_s as input is normally based on the assumed constant value.

While a ρ_s of 2.65 Mg m^{-3} can be accurate for some soils, variations in the composition of soil solids, such as an increase in SOC concentration, can significantly lower the ρ_s value since the organic fraction is an important component of soil solids. Tillage and cropping systems are not expected to considerably affect the ρ_s, but changes in SOC concentration resulting from these management systems may significantly modify ρ_s. For example, conversion of traditional tillage to reduced and no-till systems increases SOC pools (Allmaras et al., 2004; Lal, 2004; Hooker et al., 2005). Yet, the effects of such SOC increases on ρ_s have not been well documented, and the general assumption is that any change in ρ_s would be negligible. Singh et al. (1994) reported that the ρ_s for tilled soils was slightly higher than that for NT soils due to lower SOC concentration in a plowed clay loam soil. Studies comparing ρ_s values as a result of changes in SOC concentration under long-term tillage and cropping management systems are not widely documented.

Total soil porosity, an important property estimated directly from ρ_s, is widely reported when assessing soil physical quality under different tillage and cropping systems, but it is often computed with the assumed standard value of ρ_s (2.65 Mg m^{-3}), thus overlooking possible management-induced changes (e.g., Radcliffe et al., 1988; Eynard et al., 2004; Shukla et al., 2004). The reliability of data thus obtained is questionable if ρ_s within the same soil varies significantly as a function of soil management. Thus, characterization of ρ_s across contrasting management systems with differential C input for the same soil is a research priority. Implications of any changes in ρ_s due to soil management for the calculation of ρ_s-based soil properties have not been quantified.

Another important soil physical parameter that can be affected by changes in SOC concentration is the Atterberg limits, which describes the limits of soil consistency such as LL, PL, and PI. Measurement of these limits during routine analyses of agricultural soils is, however, very uncommon (Mapfumo and Chanasyk, 1998). Knowledge of soil water contents at LL and plastic limit PL is fundamental to predicting the tillage and wheel traffic effects on soil consistency. For example, plastic limit is the highest water content at which a soil can be tilled without negatively affecting its structure (Dexter and Bird, 2001; Arvidsson et al., 2004). Data on Atterberg limits are needed to assess long-term land use and tillage impacts on soil mechanical and rheological behavior (Terzaghi et al., 1988). The LL and PL of the soil depend primarily on clay and SOC concentrations (De Jong et al., 1990). The magnitude of dependence of these properties on SOC can be variable and influenced by soil texture, organic matter (OM) source, and soil–crop management. The LL and PL can be strongly, weakly, or

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H. Blanco-Canqui and R. Lal, Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, The Ohio State Univ., 210 Kottman Hall, 2021 Coffey Rd., Columbus, OH 43210-1085; W.M. Post, Environmental Science Div., Oak Ridge National Lab., Oak Ridge, TN 37831; R.C. Izaurralde, Joint Global Change Research Inst., 8400 Baltimore Ave., Suite 201, College Park, MD 20740-2496; and M.J. Shipitalo, USDA-ARS, North Appalachian Experimental Watershed, P.O. Box 488, Coshocton, OH 43812-0488. Received 23 Oct. 2005. *Corresponding author (blanco.16@osu.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: LL, liquid limit; MP, moldboard plow; NT, no-till with no beef cattle manure; NTm, no-till with beef cattle manure; OM, organic matter; PI, plasticity index; PL, plastic limit; ρ_b, bulk density; ρ_s, particle density; SOC, soil organic carbon.

not correlated with SOC concentration, depending on other properties (De Jong et al., 1990; Zhang, 1994; Mbagwu and Abeh, 1998; Joosse and McBride, 2003). In a laboratory study, Malkawi et al. (1999) reported that the PI of clay soils increased with the addition of peat, but additions >100 g kg^{-1} of SOC decreased the PI. In contrast, Zhang (1994) observed a linear decrease in the PI with additions of peat from 0 to 80 g kg^{-1} of SOC. These contradictory findings warrant further research to clarify the Atterberg limits vs. SOC relationships. The ρ_s and Atterberg limits are two fundamental soil physical properties that have not been comprehensively assessed under long-term tillage management practices with contrasting C input. Moreover, functional relationships of ρ_s and Atterberg limits with SOC concentration for long-term NT systems have not been well documented. These correlations are important to understanding the magnitude of SOC concentration effects on ρ_s and Atterberg limits.

Thus, the objectives of this study were to: (i) compare the soil ρ_s and consistency of a Rayne silt loam under five long-term (>22 yr) land use and management practices in the North Appalachian region; (ii) compare differences, if any, between the total porosity estimated from the measured ρ_s and that estimated from the assumed constant value; and (iii) determine correlations among SOC, ρ_s, and soil consistency parameters. We hypothesized that: (i) ρ_s for the same soil varies significantly with agricultural management due to differences in C input and mineralization dynamics, and its value differs from the assumed standard range, (ii) soil properties such as porosity computed using measured ρ_s values differ significantly from those computed using the assumed constant value of ρ_s within agricultural soils, and (iii) soil consistency is highly sensitive to differences in C input and can thus be used as a key indicator of management effects on the soil physical state.

MATERIALS AND METHODS

Description of the Study Site and Experimental Watersheds

This study was conducted at the USDA North Appalachian Experimental Watershed (NAEW; 40°16′19″ N, 81°51′35″ W) in Coshocton County, OH, in early May 2005. Five adjacent watersheds under long-term (>22 yr) management practices were selected for this study and included: MP, NT, NTm, pasture, and forest (Table 1). The cultivated watersheds were small (~1 ha), while the two watersheds under forest and pasture were relatively large (>1 ha). All watersheds have undulating slopes ($>10\%$). The MP, NTm, and NT watersheds were planted in continuous corn. Tillage operations were practiced on the contour in all cropped watersheds, portraying the typical farming practices in the region. The dominant species is orchardgrass (*Dactylis glomerata* L.) in the watershed under pasture, and white oak (*Querus alba* L.) and red oak (*Querus rubra* L.) in the forested watershed. Additional management details for each watershed are given in Table 1. The soil across the five watersheds is Rayne silt loam (fine-loamy, mixed, active, mesic Typic Hapludult). These soils are unglaciated and have four well-defined horizons (A, B, C, and R) developed from sedimentary rocks including coarse-grained sandstone, shale, and some limestone as dominant bedrock materials (Kelley et al., 1975).

Table 1. Management history of the small watersheds.

Treatment	Management history
Moldboard plow	22-yr continuous corn, moldboard plowed to 0.25 m deep, disked twice, and harrowed before planting.
No-till without manure	36-yr continuous corn, with pre-emergence herbicide applied for controlling weeds.
No-till with manure	42-yr continuous corn, manured with beef cattle manure at 15 Mg ha^{-1}, with pre-emergence herbicide applied for controlling weeds.
Pasture	Under perennial orchardgrass.
Forest	Under perennial hardwood forest (white and red oak).

Soil Sampling and Analyses

An area of 0.5 by 0.5 m was selected at six locations about 3 m apart within the summit position of each watershed for soil sampling. Because the watersheds at the NAEW are not replicated, the six sampling locations within the watersheds were used as pseudoreplicates for the study. Intact soil cores (7.6 cm long by 7.6 cm in diameter) were collected with a hammer-driven sampler. Bulk soil samples of ~1000 g were obtained from each sampling location at depth increments of 0 to 10, 10 to 20, and 20 to 30 cm for the determination of ρ_b, ρ_s, LL, PL, and SOC concentration before spring tillage. The ρ_b was determined by the core method and the ρ_s by the pycnometer method (Grossman and Reinsch, 2002).

The LL was determined using the Casagrande device (Campbell, 2001). The PL was determined using the "thread method" (Campbell, 2001). The PI was computed as the difference in water content between the LL and the PL. The total SOC concentration was determined by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Analysensysteme, Hanau, Germany; Nelson and Sommers, 1996). Soil samples for the determination of SOC concentration were air dried at 20°C for 72 h, gently ground, and passed through a 0.25-mm sieve. Total soil porosities were computed using the standard ρ_s (2.65 Mg m^{-3}) and measured ρ_s to test whether variations in ρ_s, if present, among management systems had significant implications for the derivation of soil porosity.

Statistical Analysis

A one-way ANOVA was used to test differences in ρ_s, ρ_b, LL, PL, PI, and SOC concentration among the five contrasting scenarios of land use and management for each soil depth. The data were analyzed assuming a randomized experiment using the six sampling locations within watersheds as pseudoreplicates. The pseudoreplication approach has been used for data analyses in numerous previous studies conducted in these watersheds (e.g., Shipitalo et al., 1997; Butt et al., 1999; Owens et al., 2002; Shukla et al., 2003; Blanco-Canqui et al., 2005). It is assumed that management treatments are mostly responsible for the differences in ρ_s, ρ_b, LL, PL, PI, and SOC concentration among watersheds because these watersheds are adjacent to each other and are within the same soil map unit. The five watersheds are arranged in a natural field block confining the five watersheds on a very similar landscape position, slope, and soil, and they have been continuously managed under the same long-term systems (>22 yr; Table 1), providing data on tillage and cropping systems in the northern Appalachians. Shukla et al. (2003) reported that differences in soil texture among these watersheds were not significant. Simple correlations and regression fits were performed to assess interrelationships among the measured soil properties. All analyses were conducted using SAS statistical software (SAS Institute, 1999).

RESULTS AND DISCUSSION

Particle Density

Soil management had a significant effect on ρ_s at all depths ($P < 0.01$; Fig. 1). The NT, NTm, and pasture treatments had significantly lower ρ_s than the MP treatment in the 0- to 10-cm depth. The ρ_s averaged across these three treatments (2.35 Mg m^{-3}) was ~7% lower than the ρ_s (2.52 Mg m^{-3}) for the MP treatment. The ρ_s was the lowest (2.33 Mg m^{-3}) under NTm for agricultural soils but did not differ significantly from that under NT and pasture treatments in the upper depth. The MP treatment had significantly higher ρ_s than the NTm treatment at all depths. The ρ_s for the MP treatment was 8.5% higher in the 0- to 10-cm depth, 7% higher in the 10- to 20-cm depth, and 4% higher in the 20- to 30-cm soil depth compared with the NTm treatment ($P < 0.01$). The ρ_s under pasture was also significantly higher by ~5% compared with NTm at the 10- to 30-cm depth. The forest soils had the lowest ρ_s of all management systems and increased from 1.79 Mg m^{-3} for the 0- to 10-cm depth to 2.40 Mg m^{-3} for the 20- to 30-cm depth ($P < 0.01$). These results are in accord with the hypothesis that ρ_s differs among agricultural systems, particularly within cultivated soils. As expected, the ρ_s increased with increasing soil depth and the magnitude of differences among treatments in the >20-cm depth was relatively small.

The higher surface ρ_s for MP than NT and pasture is supported by the results of Singh et al. (1994), who observed that plowed soils had higher ρ_s (2.49 Mg m^{-3}) than NT (2.45 Mg m^{-3}) on a clay loam, and with those of Sparling et al. (2000), who reported that plowed soils (2.60 Mg m^{-3}) had a slightly higher ρ_s than pasture (2.57 Mg m^{-3}) for a silt loam in New Zealand. Differences in ρ_s among management systems, in this study, were about four times greater than those reported by Singh et al. (1994) and Sparling et al. (2000), possibly due to differences in the duration of management. Singh et al. (1994) and Sparling et al. (2000) evaluated ρ_s in soils under <9 yr of management, whereas the soils in our study were under continuous management for >22 yr (Table 1). Long-term (>9 yr) studies comparing ρ_s between conventionally tilled and NT soils have not been widely reported. The lower ρ_s in forest vs. agricultural soils was expected due to the abundance of organic materials on forest floors. Effects of forest management on ρ_s cited in the literature are highly variable. Redding et al. (2005) reported that ρ_s for various species ranged between 1.52 and 1.60 Mg m^{-3}, which is lower than the forest ρ_s measured in this study. Other researchers (van Donk and Tollner, 2000) have also reported lower values of ρ_s (<1.52 Mg m^{-3}). These inconsistencies of ρ_s values among forest soils may be due to differences in SOC concentration, forest species, methodology, and climatic conditions.

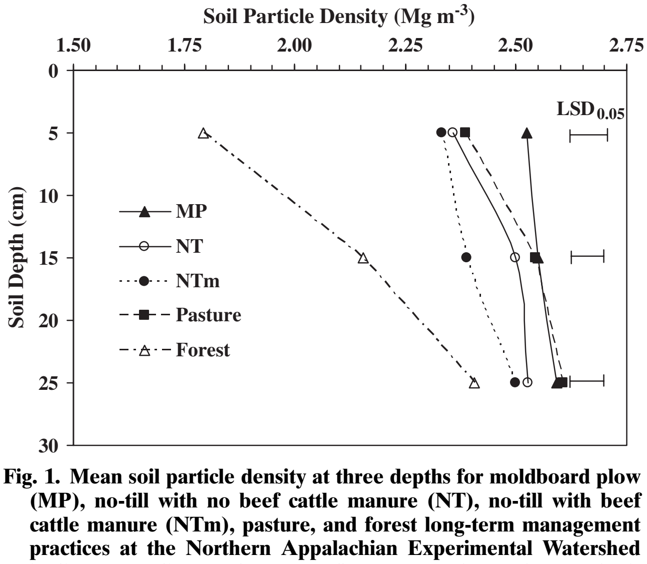

Fig. 1. Mean soil particle density at three depths for moldboard plow (MP), no-till with no beef cattle manure (NT), no-till with beef cattle manure (NTm), pasture, and forest long-term management practices at the Northern Appalachian Experimental Watershed in Coshocton County, OH. The LSD bars at a given soil depth indicate the significance of particle density among the five management practices.

The ρ_s range within agricultural soils (2.33–2.52 Mg m^{-3}) measured in the 0- to 10-cm depth for this study was consistently below the range of assumed values of 2.60 to 2.70 Mg m^{-3}. It is also lower than those reported by Singh et al. (1994) and Sparling et al. (2000). While the decrease in ρ_s from 2.52 to 2.33 Mg m^{-3} may be attributed to high input of organic residues, differences in ρ_s between MP (2.52 Mg m^{-3}) and the standard range (2.60–2.70 Mg m^{-3}) may be due to variations in parent material, chemical composition and structure of the inorganic solids, and topography. Soils of this study have steep slopes (>10%) and low sand content (<209 g kg^{-1}). Ball et al. (2000) reported that the ρ_s in sloping soils was lower than in flat terrains in Scotland, and their ρ_s ranged from 2.36 to 2.87 Mg m^{-3}. While the ρ_s for MP and pasture treatments in our study increased to ~2.60 Mg m^{-3} for the 0- to 30-cm depth, the ρ_s for NT, NTm, and forest increased to levels significantly (<2.52 Mg m^{-3}) below the assumed standard range.

Particle Density vs. Soil Organic Carbon

There were large differences in SOC concentration ($P < 0.01$; Fig. 2) among management systems at all depths. Because trends of concentration and mass of SOC were not significant, results are discussed based on SOC concentration only. The SOC concentration in the 0- to 10-cm depth increased in the order: forest > NTm > pasture > NT > MP, and the order was almost the opposite for ρ_s (Fig. 1). Thus, these significant differences in SOC concentration explain much of the difference in ρ_s. In fact, the linear regression in Fig. 3A shows that variations in SOC concentration explained ~75% of the variability in ρ_s ($P < 0.001$) in the 0- to 10-cm depth. For example, the MP management had the lowest SOC concentration and the highest ρ_s while the forest management had the highest SOC concentration and the lowest ρ_s in the 0- to 10-cm depth. These results show that changes in SOC concentration due to management can indeed have large and significant effects on

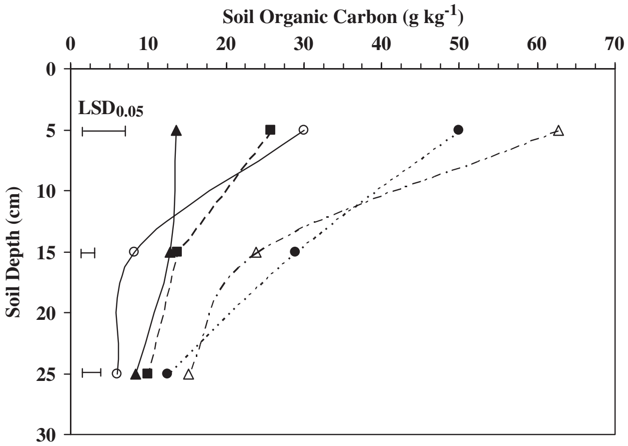

Fig. 2. Mean soil organic C concentration at three depths for moldboard plow (MP), no-till with no beef cattle manure (NT), no-till with beef cattle manure (NTm), pasture, and forest long-term management practices at the Northern Appalachian Experimental Watershed in Coshocton County, OH. The LSD bars at a given soil depth indicate the significance of soil organic C concentration among the five management practices.

ρ_s as hypothesized. Surprisingly, Fig. 3A shows that the effect of SOC concentration on ρ_s can be as large as that on ρ_b in the 0- to 10-cm depth. The r^2 values and slopes of the linear regression fits of SOC concentration vs. ρ_s and ρ_b are similar, suggesting that ρ_s is as sensitive as ρ_b to changes in SOC concentration in these soils. The decrease in ρ_s with increasing SOC concentration is attributed to the dilution effect of the mineral particles (Hillel, 1998). In this long-term study, the highly significant ρ_s vs. SOC concentration correlation ($r = -0.87$; Fig. 3A) in the 0- to 10-cm depth was much higher than that ($r < 0.50$) reported in similar studies (Ball et al., 2000). These inconsistencies may be attributed to the differences in duration and type of management practices. The ρ_s vs. SOC concentration correlation was weaker between 10 and 30 cm than the 0- to 10-cm soil depth, which is probably due to the smaller differences in SOC concentrations among management systems. The SOC concentration explained 54% of the variability in ρ_s for the 10- to 20-cm depth, and 45% for the 20- to 30-cm depth, and these correlations were significant ($P < 0.01$).

The lowest ρ_s, under NTm ($<$2.49 Mg m^{-3}), within the agricultural soils at the three depths indicates that long-term manuring ($>$42 yr) can greatly affect the profile distribution of ρ_s by lowering the ρ_s values in contrast with unmanured treatments. Manuring in interaction with lack of soil disturbance increased the SOC concentration and reduced the ρ_s (2.33 Mg m^{-3}) in the 0- to 30-cm depth even more than NT without manure ($<$2.53 Mg m^{-3}) in which ρ_s increased rapidly between 10 and 20 cm depths. These results corroborate the significant implications that manuring has for increasing the SOC concentration and altering the ρ_s with soil depth. Compared with soils under MP, those under NTm had 3.7 times higher SOC concentration for the 0- to 10-cm depth, 2.3 times higher for the 10- to 20-cm depth, and 1.5 times higher for the 20- to 30-cm depth, which probably explains the lower ρ_s under NTm. These results show that manuring increased SOC concentrations compared with MP even below the 10-cm soil depth. Similar studies assessing the combined effects of manuring vs. a NT system on ρ_s vs. SOC relationships and the depth distribution of SOC concentrations are few. Schjønning et al. (1994) reported that long-term cattle manuring ($>$90 yr) decreased ρ_b slightly from 1.64 to 1.57 Mg m^{-3} and ρ_s from 2.64 to 2.63 Mg m^{-3} in a plowed sandy loam in Denmark. The magnitude of the decrease in ρ_s in that study was not as large as in our study (2.52 vs. 2.33 Mg m^{-3}), probably due to differences in soil texture and mineralogy.

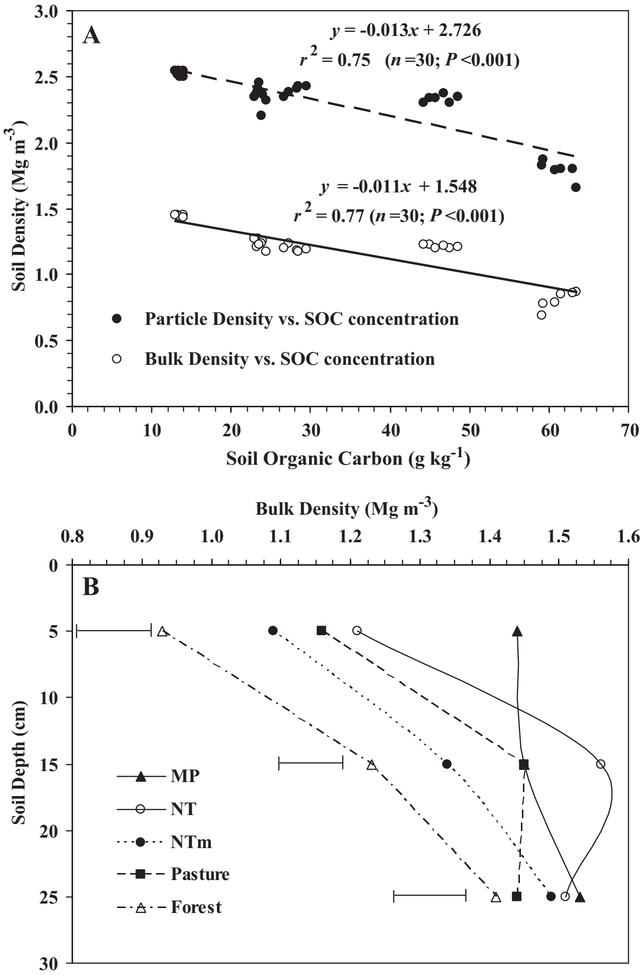

Fig. 3. (A) Relationships of bulk and particle density of soil with SOC (soil organic carbon) concentration for the 0- to 10-cm depth and (B) depth distribution of bulk density under moldboard plow (MP), no-till with no beef cattle manure (NT), no-till with beef cattle manure (NTm), pasture, and forest long-term management practices at the Northern Appalachian Experimental Watershed in Coshocton County, OH. The LSD bars at a given soil depth indicate the significance of bulk density among the five management practices.

Particle Density vs. Soil Porosity

The ρ_b, an essential input for computing soil porosity, was also significantly affected by management, particularly in the 0- to 20-cm depth (Fig. 3B). It was higher under MP than under other treatments in the 0- to 10-cm depth ($P < 0.01$). Total soil porosity computed using the standard ρ_s and measured values of ρ_s and ρ_b by management for each soil depth is shown in Fig. 4. Porosity computed using the measured ρ_s values differed significantly from that computed using the constant value of ρ_s at all depths. The variable f_{meas} was used to signify porosity computed using measured ρ_s, and f_{calc} to signify porosity computed using the standard ρ_s (2.65 Mg m^{-3}). The f_{calc} was consistently larger than f_{meas} for all management systems ($P < 0.01$). Even the f_{calc} (0.46 ± 0.005) for the MP management was slightly, but significantly, higher than the f_{meas} (0.43 ± 0.003) due to the fact that the ρ_s for the MP treatment (2.52 Mg m^{-3}) was lower than the assumed standard value of 2.65 Mg m^{-3} in the 0- to 10-cm depth. Discrepancies between f_{calc} and f_{meas} were the smallest for the MP treatment. The f_{meas} for the MP treatment was 7% lower than the f_{calc} at the 0- to 10-cm depth, while the f_{meas} for the NT, NTm, and pasture treatments were ~12% lower than the f_{calc} across the three management systems at the upper depth (Fig. 4). The f_{meas} for the forest management was 27% lower than f_{calc} in the uppermost depth. Averaged across depths, the difference between f_{calc} and f_{meas} for NT and NTm was two times as high as that for MP, which is due to the management-induced changes in ρ_s. These results show that the use of the standard ρ_s value for estimating total porosity overestimates the "true" porosity in these soils, and can thus lead to erroneous conclusions concerning management effects on total porosity. The constant value of 2.65 Mg m^{-3} may apply only to soils with both a low SOC concentration and a high presence of quartz sand fractions (Redding et al., 2005).

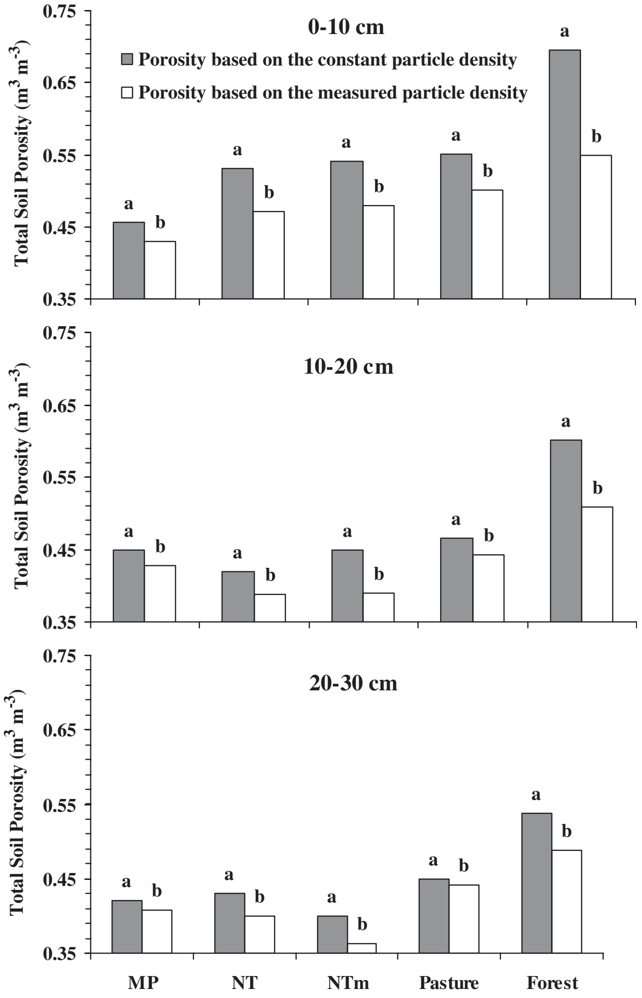

Fig. 4. Total soil porosity using assumed (2.65 Mg m^{-3}) and measured particle density for moldboard plow (MP), no-till with no beef cattle manure (NT), no-till with beef cattle manure (NTm), pasture, and forest long-term management practices at three depth intervals. Different letters within the same treatment indicate significant differences between the two porosities at the 0.05 probability level.

The data presented suggest that the results of some long-term studies of agricultural systems in which there were large and significant changes in SOC concentrations may need to be reevaluated if constant ρ_s values were used to compute total porosity. These results also emphasize the critical importance of including ρ_s in any routine characterization of soil properties while assessing the impacts of different agricultural systems on soil physical quality, given the sensitivity of ρ_s to changes in SOC concentration. While ρ_s may not be affected by soil disturbance or structural deterioration like ρ_b and other dynamic soil structural properties, it can be significantly altered by changes in SOC concentration. Additional comparison of ρ_s effects on soil porosity across diverse management practices and soils are needed to further understand the magnitude of changes.

Atterberg Limits

Soil management had a significant impact on the Atterberg limits also, particularly in the 0- to 20-cm soil depth (Fig. 5). Differences in water content at the LL among the five treatments were large for the 0- and 20-cm depth and increased in the order: NTm > forest > pasture > NT > MP. The soil water content at the LL for NTm soils was 6% higher than for forest, 24% higher than for pasture, 33% higher than for NT, and 85% higher than for MP soils. Water content at the PL in the 0- and 10-cm depth increased in the order: NTm = forest > pasture = NT > MP. At the PL, NTm and forest treatments retained 30% more water than pasture and NT and 100% more than MP, while pasture and NT retained 55% more water than MP. At the 10- to 20-cm depth interval, NTm and forest retained ~36% more water at the PL than the rest of treatments. Differences in the PI among management systems were smaller than those in the LL and the PL. The NTm management had a significantly higher PI than NT and MP at the three depths. No significant differences in the PI were observed among NTm, forest, and pasture treatments, but the value of the PI averaged across these three management systems was 23% higher than that for NT and 84% higher than that for the MP treatment in the 0- to 10-cm depth. At the 10- to 20-cm depth, the PI for NTm was 16% higher than that for pasture, 42% higher than that for NT, and 92% higher than that for MP. While differences in the PI between NTm and forest were not significant in the 0- to 20-cm depth, the PI for NTm was 50% higher than that for the forest management in the 20- to 30-cm depth.

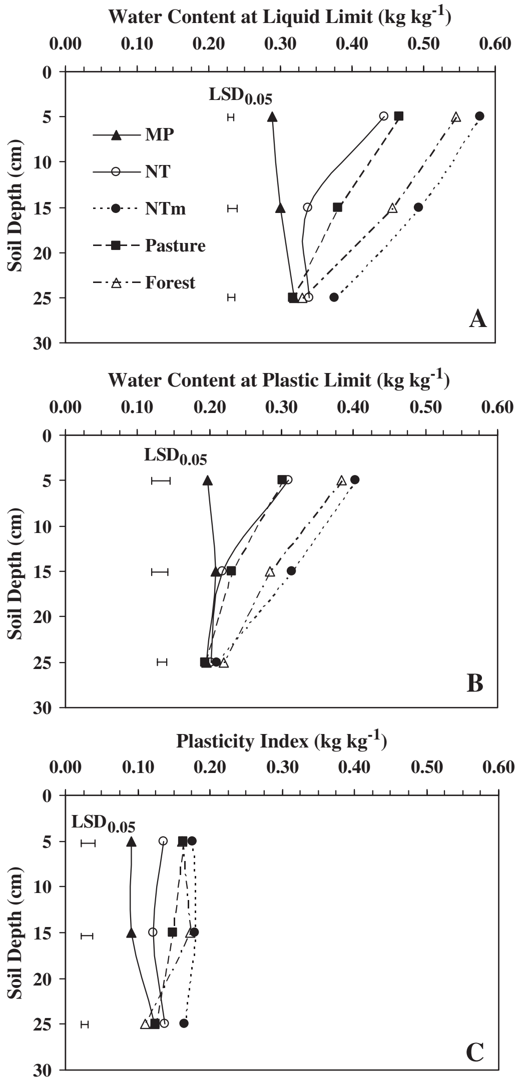

Fig. 5. Soil water contents at the liquid limit (LL), plastic limit (PL), and plasticity index (PI) for three soil depths for moldboard plow (MP), no-till with no beef cattle manure (NT), no-till with beef cattle manure (NTm), pasture, and forest long-term management practices at the Northern Appalachian Experimental Watershed in Coshocton County, OH. The LSD bars at a given soil depth indicate the significance of LL, PL, and PI among the five management practices.

These results show that management significantly affected the soil consistency at all depths. No-till in combination with manuring had a strong effect on increasing the LL, PL, and PI values. The water retention values for the PI, LL, and PL constants under NTm were ~30% higher than those under NT alone, indicating that manured NT soils had better soil structure or consistency. Manure supplies OM and improves the water retention capacity of the soil (Arriaga and Lowery, 2003). The higher LL and PI for NTm than for forest in the 20- to 30-cm depth interval suggest that manure additions may stabilize the soil better than forest-derived organic materials at lower depths. Because the Atterberg constants were highly sensitive to management, they could be used as indicators of soil physical quality for long-term land use and management systems for these and similar soils. The consistency limits are important parameters related to soil structural stability (Marinissen, 1994). Indeed, Watts and Dexter (1998) stated that the PL in particular is a useful index of soil physical quality. For instance, the higher PL value for NTm in our study indicates that soils under this management have better physical structure than under the other agricultural systems in this study.

The study results also show the merit of measuring the Atterberg limits for determining the optimum water content for tillage. The large differences in LL, PL, and PI suggest that the optimum water content for tillage varies significantly among the selected cultivated watersheds. When the soil is too wet, tillage operations can have detrimental effects on soil structure (Mueller et al., 2003). The knowledge of differences in soil consistency limits can allow a better scheduling of tillage operations and traffic. Mueller et al. (2003) identified the PL as one of the most sensitive parameters to estimate the highest water content for optimum tillage across a broad range of soils. The higher PL value indicates that these soils are trafficable even at higher water contents under NTm and NT than under MP land use. In other words, MP soils are prone to vehicle-induced compaction at water contents lower than NTm and NT soils. The PL under NTm soils was two times as high as under MP. Soil macro- and microstructural properties can be significantly altered by untimely tillage ignoring the dynamics of soil consistency (Adam and Erbach, 1992; Barzegar et al., 2004).

Atterberg Limits vs. Soil Organic Carbon

The significant differences in soil consistency were attributed to variations in SOC concentration with management systems. The water contents at LL and PL including the PI followed a quadratic relationship with SOC concentration in the 0- to 10-cm depth (Fig. 6A). Variations in the SOC concentration explained 98% of the variability in the LL, 93% in the PL, and 68% in the PI. These strong correlations show that management-induced changes in the SOC concentration have a strong effect on soil consistency. Unlike studies by De Jong et al. (1990) and Zhang (1994), who reported variable correlations, in our study soil consistency was highly correlated with the SOC concentration. The positive correlations in this study, however, support the conclusion of Odell et al. (1960), who reported that LL, PL, and PI were all positively correlated with the SOC concentration. The significant PI vs. SOC correlations reported by Odell et al. (1960) and by our study contrast with the study by Ball et al. (2000), who reported no significant dependence of PI on SOC concentration. These inconsistencies may be due to differences in soil inherent characteristics such as management duration, soil parent material, clay content and mineralogy, and the type and nature of the OM (De Jong et al., 1990).

The quadratic regression curves in Fig. 6A for the LL and PL increased rapidly up to ~48 g kg^{-1} of SOC and then decreased slightly with a further increase in the SOC concentration. The decline of water contents after ~48 g kg^{-1} of SOC may be due to the qualitative

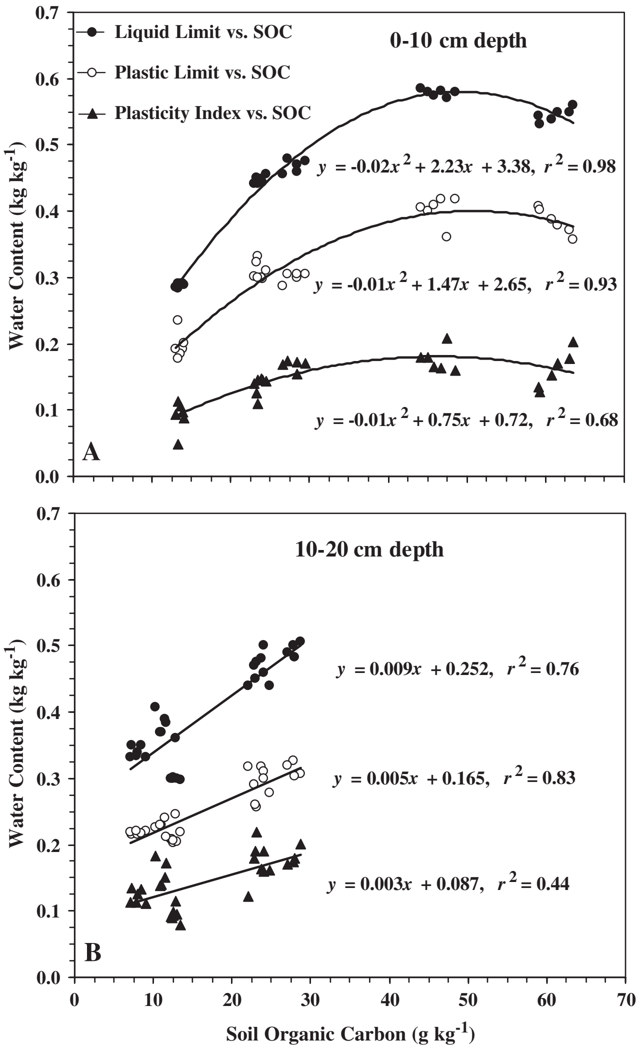

Fig. 6. Liquid limit, plastic limit, and plasticity index as a function of soil organic carbon (SOC) concentration for the (A) 0- to-10-cm and (B) 10- to-20-cm soil depths across five long-term management practices at the Northern Appalachian Experimental Watershed in Coshocton County, OH. The r^2 were all significant at the 0.001 probability level.

differences in the OM between the agricultural and forest soils. We hypothesize that the OM in the agricultural soils may be strongly associated with the mineral fraction, which would account for its effect on soil consistency, whereas the OM in the forest soil was probably less closely associated with the mineral fraction. The increase in the LL and PL with increasing SOC concentration is probably due to the high surface area of the organic materials. The LL, PL, and PI increased linearly with increasing SOC at low concentrations (<30 g kg^{-1}) for the 10- to 20-cm depth ($P < 0.01$; Fig. 6B). At this depth, the SOC concentration explained ~76% of the variability in the LL, 83% in the PL, and 44% in the PI. At the 20- to 30-cm depth, the SOC concentration was not significantly correlated with Atterberg limits except the PI, where changes in the SOC concentration explained about 70% of the variability in the PI. As with ρ_s, the lower correlation coefficients at lower depths could be attributed to the decrease in SOC concentrations. At lower depths, increases in clay content may play a dominant role in explaining changes in the consistency limits.

CONCLUSIONS

Soil particle density and consistency (Atterberg limits) were significantly affected by land use and management practices across five watersheds on a Rayne silt loam in the northern Appalachians. No-till management, particularly in combination with manure, decreases the ρ_s and increases soil consistency significantly compared with MP due to differential C input. Total porosity computed using the constant value (2.65 Mg m^{-3}) of ρ_s significantly overestimates the "true" porosity, thereby suggesting the need to measure ρ_s values to reliably compute related soil properties. The Atterberg limits can be sensitive parameters to evaluate the physical condition of soils because of large differences among management systems. Results also suggest that measurement of ρ_s and soil consistency must be included in any routine soil tests because these soil properties can differ significantly among management practices. Both ρ_s and Atterberg limits were significantly influenced by management-induced changes in SOC concentrations. Since improved soil conservation practices such as reduced tillage and no-till in combination with manuring for promoting SOC sequestration are being increasingly adopted, additional studies are needed to further understand the effects of contrasting and enhanced management systems on ρ_s and related soil parameters.

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