### Strength Properties and Organic Carbon of Soils in the North Appalachian Region

H. Blanco-Canqui,\* R. Lal, L. B. Owens, W. M. Post, and R. C. Izaurralde

### **ABSTRACT**

Soil strength influenced by management and soil properties controls plant growth, root development, and soil-moisture relations. The impact of textural and structural parameters on soil strength is moderated by soil organic C (SOC) concentration. Therefore, the objectives of this study were to assess differences in soil strength and SOC concentration in watersheds under long-term (>15 yr) management practices in the North Appalachian region on a predominantly Typic Hapludults on undulating slopes (>6% slope). Seven watersheds without field replication under moldboard plow (MP), chisel plow, disk with beef cattle manure (DiskM), no-till with beef cattle manure (NTm), no-till with no beef cattle manure (NTnm), pasture, and forest were studied. Cone index (CI), shear strength, bulk density (ρ<sub>b</sub>), volumetric moisture content  $(\theta_v)$ , and SOC concentration were determined at the summit, backslope, and footslope landscape positions at the 0- to 10-, 10- to 20-, and 20- to 30-cm depths. The SOC concentration was slightly higher at the footslope than at the summit position in the cultivated watersheds. The  $\rho_b$  was lower at the footslope than at the summit in NTm (1.22 vs. 1.42 Mg  $m^{-3}\!)$  and chisel (1.34 vs. 1.47 Mg  $m^{-3}\!)$ treatments. Forest had the lowest CI (0.19 MPa), shear strength (6.11 kPa), and  $\rho_b$  (0.93 Mg m<sup>-3</sup>) and the highest SOC concentration (62.7 g kg<sup>-1</sup>), whereas MP had the highest CI (0.67 MPa), shear strength (25.5 kPa),  $\rho_b$  (1.44 Mg m<sup>-3</sup>), and the lowest SOC concentration (13.6 g  $kg^{-1}$ ) in the 0- to 10-cm depth (P < 0.01). The SOC concentration in NTm was 1.7 times higher than that in NTnm, and both no-till treatments had lower  $\rho_b$  (<1.21 Mg m<sup>-3</sup>) than MP (1.44 Mg m<sup>-3</sup>) at 0- to 10-cm depth (P < 0.01). Manuring decreased both CI and shear strength, but increased SOC concentration. The  $\rho_b$ ,  $\theta_v$ , and SOC concentration were potential predictors of CI; whereas ρ<sub>b</sub> and SOC concentration were of shear strength ( $r^2 > 0.42$ ; P < 0.01). Results show that landscape positions had small effect, but management, particularly manuring, had large and significant effects on soil strength and SOC concentration.

Land use and management practices impact soil strength, the capacity of soil to withstand external or internal forces without being mechanically compacted or fragmented. Soil strength is one of the most dynamic soil mechanical properties, and its knowledge is important to tilth, plant growth, and soil biological activity. High soil strength limits root growth and reduces crop production (Busscher and Bauer, 2003). It also reduces hydraulic conductivity and infiltration, in-

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Published in Soil Sci. Soc. Am. J. 69:663–673 (2005). doi:10.2136/sssaj2004.0254 © Soil Science Society of America 677 S. Segoe Rd., Madison, WI 53711 USA creases runoff and soil losses, and thus adversely affects environmental quality (Gómez et al., 1999).

Cone index and in situ shear strength are two intrinsic parameters related to soil strength. Characterization of CI is a common approach used for assessing soil strength dynamics, but the effects of soil management on CI are highly variable. For example, soils under MP may have a higher (Larney and Kladivko, 1989; Busscher et al., 1997), equal (Hao et al., 2000; Vetsch and Randall, 2002), or lower (Hill, 1990; Stelluti et al., 1998) CI than those under no-till or chisel plow systems, depending on soil, time to last tillage operation, and site properties. Cassel et al. (1995) reported that NT and chisel plow had a lower CI than MP in trafficked interrows, but the opposite was true in the untrafficked interrows for the surface layer of a sandy clay loam.

In situ shear strength, which is the maximum resistance of soil to shear, is a dynamic indicator of structural behavior, but its measurement is often ignored in field research when assessing effects of management on soil properties (Silva et al., 2004). Knowledge of shear strength dynamics, however, is crucial to understanding the mechanical behavior and structural sustainability of agricultural soils. Management changes the resistance of soil to shearing stresses. Silva et al. (2004) observed that soil shear strength in MP was higher than that in reduced tillage systems in a clayey soil, while Cotching et al. (2002) observed that soils under MP had lower shear strength than those under pasture of similar texture.

The CI and shear strength depend on soil moisture content (Hill, 1990), SOC concentration (Watts and Dexter, 1997), soil physical properties (Grunwald et al., 2001), other management-induced soil attributes (Cassel et al., 1995), and on the time of measurement. The CI and shear strength are usually lower in MP than those in NT soils immediately after tillage or early in the growing season, but these differences between MP and NT are transient and often disappear later in the season (Vetsch and Randall, 2002). Large pores created by tillage collapse rapidly because of soil recompaction, rainfall-induced consolidation, and reduction in SOC concentration (Katsvairo et al., 2002). The dynamic fluctuations of strength properties particularly in tilled soils add complexity to their quantification.

The SOC concentration influences soil strength dynamics by modifying the cohesiveness of soil particles and structural stability. Contrasting input of crop residues among management practices impacts SOC concentration and soil strength. The response of soil strength to manuring and crop residues is somewhat mixed. Soils

**Abbreviations:** CI, cone index; DiskM, disk with beef cattle manure; MP, moldboard plow; NAEW, North Appalachian Experimental Watershed; NTm, no-till with beef cattle manure; NTnm, no-till with no beef cattle manure; PTFs, pedotransfer functions;  $\rho_b$ , bulk density; SOC, soil organic carbon;  $\theta_v$ , volumetric moisture content.

high in SOC concentration may have increased (Gómez et al., 1999), unchanged (Hulugalle and Entwistle, 1997), or decreased (Mosaddeghi et al., 2000) CI. Effects of SOC on shear strength are also unclear. Davies (1985) reported that shear strength increased with an increase in SOC concentration in a clay loam soil. Similarly, Schjønning et al. (1994) reported that manured soils had the highest shear strength in a sandy loam soil. In contrast, Ohu et al. (1986) observed that shear strength decreased with SOC concentration in a clay, sandy loam, and clay loam soil. Similarly, Watts and Dexter (1997) found that shear strength decreased with increase in SOC concentration in a fine silt loam soil.

Management effects on soil strength properties have been reported for a number of soils (Busscher et al., 1997; Stelluti et al., 1998; Watts and Dexter, 1997; Silva et al., 2004). However, information on strength properties for the soils of the North Appalachian region in Ohio is scanty. Yet, there is a need to improve the understanding of the interactive effects of long-term soil management and landscape characteristics on soil strength and SOC differences in these soils to formulate appropriate management practices. Literature shows that soil strength response to SOC concentration and tillage may vary by soil and management. The distribution of SOC concentration and soil strength behavior may also be influenced by landscape position within the same soil (Zebarth et al., 2002). Changes in SOC concentration due to differences in management can have profound influence on soil structural characteristics (Watts and Dexter, 1997). However, few studies have assessed the relations between soil strength and SOC concentration for a range of longterm management options (Kay et al., 1997).

Thus, the objectives of this study were to (i) determine differences in soil strength and SOC concentration in watersheds under diverse land use and management practices, (ii) assess the impact of landscape position and soil depth on soil strength and SOC concentration, and (iii) formulate empirical relationships between SOC and soil strength for a range of soil physical properties. The general hypothesis is that soil strength is significantly influenced by management-induced differences in SOC concentration and soil moisture regime, and the sensitivity of soil strength to differences in SOC concentration can be assessed using pedotransfer functions (PTFs), which are useful tools for studying site-specific SOC vs. soil strength

dynamics (Kay, 1998). The specific hypotheses tested were that both CI and shear strength are sensitive to: (i) soil management and landscape position, and (ii) SOC concentration in relation to long-term soil management practices.

#### MATERIALS AND METHODS

### **Study Site**

The experiment was conducted at the USDA North Appalachian Experimental Watershed (NAEW) in Coshocton County, OH in early spring, 2004. The NAEW, established in the late 1930s, is located about 16 km northeast of the City of Coshocton, OH. It is one of the first watershed research stations in the USA and covers an area of about 400 ha comprising uplands intermixed with narrow and steep valleys. Cropping and tillage practices at the NAEW have been practiced on undulating slopes (approximately 12% slope), portraying the typical farming practices in the region. Average annual precipitation at the NAEW is 950 mm of which about 200 mm is received during the winter between December and March, and evapotranspiration exceeds precipitation between June and October. The soils at the site are unglaciated and have four well-defined horizons (A, B, C, and R) developed from sedimentary rocks including coarse-grain sandstone, shale, and some limestone as dominant bedrock materials. The major parent materials are residuum and colluvium derived from the sedimentary bedrock (Kelley et al., 1975).

### **Description of the Experimental Watersheds**

Seven watersheds under long-term (>15 vr) management practices were selected for the study and included: moldboard plow (MP), chisel plow, disk with beef cattle manure (DiskM), no-till with beef cattle manure (NTm), no-till with no beef cattle manure (NTnm), pasture, and forest (Table 1). The five cultivated watersheds were small (<1 ha), while the two watersheds under forest and pasture were relatively large (>1 ha). All watersheds have undulating slopes (>6% slope) except the one under the MP treatment (0.2% slope; Table 2), which is also the smallest watershed (0.12 ha) sited on the summit position. The MP, NTm, and NTnm were managed under continuous corn (Zea mays L.). The chisel treatment was cropped to corn-soybean (Glycine max L.)/rye (Secale cereale L.) rotations where rye was used as a winter cover crop, while the disk treatment was cropped to corn-soybean, and wheat (Triticum aestivum L.)/red clover (Trifolium pretense L.) rotation. Tillage operations were practiced on the contour in all watersheds. The dominant species in the watershed under pasture is orchardgrass (Dactylis glomerata L.), and under

Table 1. Management history of the seven watershed treatments at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Treatment†	Management history
MP	21-yr continuous corn (Zea mays L.), moldboard plowed to 0.25-m depth, disked twice, and harrowed before planting; 150 kg N ha $^{-1}$ applied as NH <sub>4</sub> NO <sub>3</sub> .
Chisel	15-yr corn-soybean ( <i>Glycine max</i> L.)/rye ( <i>Secale Cereale</i> L.) rotation, chisel plowed to 0.25 m at 0.30-m spacing in spring, and 150 kg N ha <sup>-1</sup> applied as NH <sub>4</sub> NO <sub>3</sub> in corn year.
DiskM	15-yr wheat ( <i>Triticum aestivum</i> L.)/red clover ( <i>Trifolium pretense</i> L.)-corn-soybean rotations, shallow disking before planting. 14 Mg ha <sup>-1</sup> of beef cattle manure each spring and 90 kg N ha <sup>-1</sup> applied as NH <sub>4</sub> NO <sub>3</sub> every 3 yr during corn rotation. The last manure application was in 2003, 1 yr before this study.
NTm	41-yr continuous corn, manured with beef cattle manure each spring at 15 Mg ha <sup>-1</sup> , 150 kg N ha <sup>-1</sup> applied as NH <sub>4</sub> NO <sub>3</sub> , and herbicides applied for controlling weeds.
NTnm	35-yr continuous corn, 150 kg N ha <sup>-1</sup> applied as NH <sub>4</sub> NO <sub>3</sub> , and herbicides applied for controlling weeds.
Pasture	Perennial orchardgrass (Dactvlis glomerata L.).
Forest	Perennial hardwood forest (white [Ouercus alba L.] and red oak [Ouercus rubra L.]).

<sup>†</sup> MP, moldboard plow; DiskM, disk with beef cattle manure; NTm, no-till with beef cattle manure; NTnm, no-till with no beef cattle manure.

Table 2. Classification of soils in the seven watershed treatments at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Treatment†	Soil Series	Soil Classification	Slope
			%
MP	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	$\sim$ 0.2
Chisel	Keene silt loam	Fine-silty, mixed, mesic Aquic Hapludalfs	7
DiskM	Coshocton-Rayne silt loams	Fine loamy, mixed, mesic Aquic Hapludalfs; Typic Hapludults	12-18
NTm	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	6–12
NTnm	Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	6–12
Pasture	Summit: Rayne silt loam	Fine loamy, mixed, mesic Typic Hapludults	12-18
	Backslope: Berks shaly silt loam	Loamy skeletal, mixed, mesic Typic Dystrochrepts	18-23
	Footslope: Coshocton-Rayne silt loam	Fine loamy, mixed, mesic Aquic Hapludalfs; Typic Hapludults	12-18
Forest	Coshocton-Rayne silt loams	Fine loamy, mixed, mesic Aquic Hapludalfs	18-25

† MP, moldboard plow; DiskM, disk with beef cattle manure; NTm, no-till with beef cattle manure; NTnm, no-till with no beef cattle manure.

forest is white oak (*Quercus alba* L.) and red oak (*Quercus rubra* L.). Further management details for each watershed are given by Owens et al. (2002) and Shukla et al. (2003). Soil series and taxonomic classification differ among the watersheds but all have silt loam surface texture. The Rayne series (fine-loamy, mixed, active, mesic Typic Hapludults) is the dominant soil in four watersheds and is characterized by better drainage than other series because it has less clay content in the B horizons (Kelley et al., 1975). Further information on soil and watershed management is presented in Tables 1 and 2.

### **Determination of Cone Index and Shear Strength**

Soil penetration resistance and shear strength were measured between 15 and 17 Mar. 2004, about 1 yr after the last tillage operation performed in April 2003. Tillage operations in these watersheds are performed in spring, either in late April or early May, depending on weather conditions. Soil penetration resistance and shear strength were determined at the summit, backslope, and footslope landscape positions within each watershed to account for the spatial variability except in the MP treatment, which was confined to the summit position only. An area of 0.5 by 0.5 m was selected at three locations about 3 m apart within each landscape position for the CI and shear strength determinations. A static hand cone penetrometer (Eijkelkamp, Giesbeek, The Netherlands) was used for the measurements of soil penetration resistance (Bradford, 1986). The penetrometer was pushed downward steadily and vertically at about 1 cm s<sup>-1</sup>. Measurements were made in triplicate for the 0- to 10-, 10- to 20-, and 20- to 30-cm depths. Cone index was computed by dividing the manometer reading by the base area of the cone and expressed in MPa.

In situ shear strength was measured using a hand shear vane tester (Serota and Jangle, 1972). A CL-612 shear vane tester (ELE International, Inc. Lake Bluff, IL) with a 1.9-cm vane diameter and a 15.2 cm long spindle coupled to a torque was used. The shear strength was measured by gradually revolving the torque clockwise at about 0.2 cm s<sup>-1</sup> while increasing the lateral and tangential stress until failure occurred. Three measurements were made at random points for each landscape position. Shear strength (in kPa) was also measured for the 0- to 10-, 10- to 20-, and 20- to 30-cm depths.

### **Soil Sampling and Laboratory Measurements**

Bulk soil samples (500 g) were collected at the time of soil penetration resistance and shear strength determinations from all landscape positions and watersheds for the determination of SOC concentration. Intact soil cores (5.3 cm diam. by 6 cm deep) were taken for soil moisture content and bulk density determinations. A double-cylinder hammer-driven sampler was used to collect soil cores manually. Triplicate samples were obtained for the 0- to 10-, 10- to 20-, and 20- to 30-cm depths

for a total of 171 cores and 171 bulk samples (3 depths  $\times$  3 replicates  $\times$  3 landscape positions  $\times$  6 watersheds = 162 samples plus 3 depths  $\times$  3 replicates for MP watershed = 9). Samples were sealed in plastic bags, transported to the laboratory, and their moisture content determined gravimetrically (Gardner, 1986). Bulk density ( $\rho_b$ ) was determined using the core method (Blake and Hartge, 1986). Volumetric moisture content ( $\theta_v$ ) was computed based on the gravimetric moisture content ( $\theta_g$ ) and  $\rho_b$  data. The bulk samples were air-dried, and a fraction of the air-dried samples was ground and passed through sieves with 0.25-mm openings for the determination of SOC concentration by the dry combustion method (900°C) using a CN analyzer (Vario Max, Elementar Americas, Inc., Germany; Nelson and Sommers, 1996).

### **Adjustment of Soil Strength Parameters**

Soil strength parameters were adjusted to a common value of soil gravimetric moisture content ( $\theta_{gc}$ ) to eliminate the dependence of CI and shear strength (SHEAR) on the measured gravimetric moisture content ( $\theta_{gi}$ ) for all management practices. An approach based on a Taylor series developed by Busscher et al. (1997) was used for the corrections as

AdjustedCI = InitialCI + 
$$\frac{\partial CI}{\partial \theta_{g}} (\theta_{gc} - \theta_{gi})$$
 [1]

AdjustedSHEAR = InitialSHEAR +

$$\frac{\partial SHEAR}{\partial \theta_{o}} \left( \theta_{gc} - \theta_{gi} \right) \tag{2}$$

where  $\partial CI/\partial \theta_g$  and  $\partial SHEAR/\partial \theta_g$  are the first derivative of the regression fits of either CI or shear strength, on soil moisture content vs. CI or shear strength. A power model produced the best fit for all the data points (n=171) across treatments, landscape positions, and depths as follows:

CI vs.
$$\theta_g$$
: CI = 0.11 $\theta_g^{-1.17}$   $r^2$  = 0.53 ( $P$  < 0.01) [3] SHEAR vs.  $\theta_g$ : SHEAR = 6.20 $\theta_g^{-1.08}$ 

$$r^2 = 0.47 \ (P < 0.01)$$
 [4]

The first derivatives of the best-fit functions shown in Eq. [3] and [4] across treatments, positions, and depths were used in Eq. [1] and [2], respectively. The strength parameters were adjusted to moisture content of 0.25, as an arbitrary value for the  $\theta_{\rm gc}$ . The *r*-square values for the best fits in Eq. [3] and [4] were relatively low but significant because the number of observations was large (n = 171). The low *r*-squares are explained by the fact that the relationship between CI and shear strength vs.  $\theta_{\rm gi}$  varied with treatment (Table 3). The best-fit equations between strength vs.  $\theta_{\rm gi}$  were highly significant for the DiskM, NTm, NTnm, and forest but equations for the MP and chisel management systems were not.

Table 3. Best-fit equations between soil strength and gravimetric moisture content ( $\theta_g$ ) for the seven treatments at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Treatments†	Cone index equation	<u>r³</u>	Shear strength equation	<u>r</u> <sup>2</sup>
MP	$0.74 - 0.35\theta_{g}$	0.02	$-2.89 + 104.75\theta_{g}$	0.18
Chisel	$1.48 - 3.120^{\circ}$	0.09	$53.61 - 97.830_{\circ}$	0.08
DiskM	$0.020^{-2.54}$	0.74**	$5.510^{-1.26}$	0.70**
NTm	$0.09\theta_{g}^{5-1.78}$	0.86**	$5.690_{g}^{5-1.16}$	0.69**
NTnm	$0.160_{g}^{5-1.45}$	0.87**	$7.320^{5-1.25}_{9}$	0.80**
Pasture	$0.180^{\circ}_{g}^{-1.12}$	0.42**	40.98 - 33.460	0.10
Forest	$0.08\theta_{\rm g}^{\rm s}$ 1.15	0.52**	$2.040_{\rm g}^{-1.39}$	0.56**

<sup>\*\*</sup> Significant at the 0.01 probability level.

### **Statistics**

The watersheds at the NAEW are not field replicated. However, all watersheds are sited on a similar landscape position, slope, and soil, and they have been continuously managed under the same treatments (>15 yr; Table 1) providing data on longterm tillage and cropping systems reported in numerous studies (Butt et al., 1999; Owens et al., 2002; Shukla et al. (2003) among others). Because of the lack of field replication, the three selected sampling locations in each landscape position (summit, backslope, and footslope) within watersheds were used as pseudo replicates for the statistical analysis, and the analysis was treated as if it were a randomized experiment. Recognizing that this procedure may not fully separate the effects of inherent differences among watersheds on the measured soil properties from the management-induced differences, it is supposed that management treatments are at least partly responsible for the differences in soil properties among watersheds because the relative differences in most soil properties among management systems were large.

Normality test of the residuals for each measured property showed that data were normally distributed (P < 0.01). Statistics on CI and shear strength values were performed on the adjusted data. Analysis of variance (ANOVA) of one-factor model was used to test the hypothesis that differences in CI, shear strength,  $\rho_b$ ,  $\theta_v$ , and SOC concentration among the management practices were the same by depth. Effect of landscape positions on soil properties was tested using one-factor model for each management practice. Analyses were done using SAS statistical software (SAS Institute, 1999). Comparison of MP with the rest of the treatments was performed only for the summit position. Correlation and stepwise multiple regression analyses were conducted to derive PTFs for predicting the CI and shear strength values for each treatment and for all the data points using a combination of  $\rho_b$ , SOC concentration, and  $\theta_v$  data as independent predictor variables. The CI and shear strength are both measures of soil strength, thus these variables were not used in the same predictive function to develop PTFs. Statistical differences between concentration and pool of SOC were nonsignificant, thus results are discussed based on SOC concentration only.

## RESULTS AND DISCUSSION

### **Landscape Position**

The response of the selected properties to landscape position differed among soil properties and management practices (Table 4). The effect of position on CI, and shear strength was smaller than that on SOC con-

Table 4. Selected soil properties as a function of landscape position and management practices including chisel plow, disk with beef cattle manure (DiskM), no-till with beef cattle manure (NTm), no-till with no beef cattle manure (NTnm), pasture, and forest at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Position	Chisel	DiskM	NTm	NTnm	Pasture	Forest	LSD(0.05)
			Organic C cond	centration, g kg <sup>-1</sup>			
Summit	10.91	15.49	27.10	12.62	15.80	33.42	10.81
Backslope	10.40	15.80	28.51	14.40	18.70	33.50	12.23
Footslope	13.41	16.50	35.80	17.23	15.05	33.43	13.70
LSD(0.05)	2.11	6.68	16.89	12.12	7.54	22.50	
			Organic	C, Mg ha <sup>-1</sup>			
Summit	16.08	22.29	36.18	17.02	20.47	30.64	10.04
Backslope	15.28	23.02	34.63	18.30	25.45	35.38	11.22
Footslope	18.02	22.61	40.36	22.50	18.62	35.53	13.20
LSD(0.05)	1.71	8.12	16.30	13.49	7.77	18.57	
			Bulk dens	ity, Mg m <sup>-3</sup>			
Summit	1.47	1.46	1.42	1.43	1.35	1.36	0.12
Backslope	1.43	1.49	1.29	1.43	1.38	1.19	0.16
Footslope	1.34	1.41	1.22	1.41	1.32	1.02	0.17
LSD(0.05)	0.05	0.11	0.19	0.18	0.16	0.22	
			Cone in	dex, MPa			
Summit	0.70	0.73	0.93	0.99	0.59	0.46	0.30
Backslope	0.53	0.56	0.80	1.27	0.84	0.34	0.34
Footslope	0.88	0.49	0.81	1.27	0.98	0.50	0.34
LSD(0.05)	0.20	0.31	0.47	0.41	0.39	0.26	
			Shear str	ength, kPa			
Summit	26.86	30.82	22.63	34.76	31.61	14.11	8.30
Backslope	22.78	28.94	26.31	46.31	26.00	13.67	9.11
Footslope	31.72	28.44	25.82	40.60	34.44	17.56	10.31
LSD(0.05)	5.10	8.93	10.89	13.76	9.54	9.33	
		•	Volumetric moistur	e content, mm³ mn	$1^{-3}$		
Summit	0.37	0.37	0.37	0.39	0.45	0.33	0.04
Backslope	0.36	0.41	0.39	0.38	0.34	0.35	0.06
Footslope	0.39	0.42	0.41	0.38	0.43	0.29	0.06
LSD(0.05)	0.02	0.05	0.07	0.06	0.06	0.07	

<sup>†</sup> LSD = Least significance difference at the 0.05 probability level.

<sup>†</sup> MP, moldboard plow; DiskM, disk with beef cattle manure; NTm, notill with beef cattle manure; NTnm, no-till with no beef cattle manure.

centration and  $\rho_b$ . Differences in shear strength among positions were not significant. Soil  $\rho_b$  was significantly lower at the footslope than at the summit in NTm (1.22 vs. 1.42 Mg m<sup>-3</sup>) and chisel (1.34 vs. 1.47 Mg m<sup>-3</sup>) treatments (Table 4). The footslope in NTnm and DiskM tended to have lower  $\rho_b$ , but differences among treatments were not significant. The  $\theta_v$  on the footslope was significantly higher than on the summit only in the DiskM treatment.

The SOC concentration on the footslope was 1.3 times higher than that on the backslope and summit positions in the chisel treatment (P < 0.05; Table 4). While the position effect on SOC concentration for other treatments was small, the SOC concentration was the highest at the footslope and lowest at the summit positions in NTm (35.8 vs. 27.1 g kg<sup>-1</sup>), NTnm (17.2 vs. 12.6 g kg<sup>-1</sup>), and DiskM (16.5 vs. 15.5 g kg<sup>-1</sup>). As expected, these results indicate deposition of SOC at footslope positions through erosion, and farming is a primary factor for the uneven distribution concentration of SOC with position because differences in SOC concentration with position occurred only in cropped watersheds. Pierson and Mulla (1990) also reported that soil erosion transferred SOC from the ridgetops to lower positions, thus changing the patterns of SOC redistribution on a Palouse silty clay loam. Similarly, Zebarth et al. (2002) reported that lower positions of tilled soils had significantly higher SOC concentration than upper positions in a loamy soil in Canada. Results suggest that the low  $\rho_b$  values at the footslopes may be attributed to the high SOC concentration at this position, which often reduces  $\rho_h$  and improves soil moisture retention. The data also suggest that SOC and landscape position relationships must be considered when assessing SOC storage in sloping lands (Vanden-Bygaart et al., 2002). Indeed, McCarty and Ritchie (2002), while studying the impact of agricultural activity on SOC distribution, reported that deposition of SOC with eroded sediments represents a major potential for SOC sequestration in cultivated watersheds. In rolling landscapes, landform can be an important site-specific factor controlling the transfer, redistribution, and storage of SOC in interaction with long-term management systems.

### **Soil Strength Properties**

The effect of management on soil strength properties (CI and shear strength) was highly significant at all depths, but differences among management practices varied by depth (Table 5; Fig. 1). At 0- to 10-cm depth, forest had the lowest CI (0.19 MPa) and shear strength (6.11 kPa: P < 0.01): whereas MP (0.67 MPa) had the highest CI followed by NTnm (0.64 MPa; P < 0.01). The CI was in the order: MP = NTnm > Chisel > Pasture > NTm = DiskM > Forest, while shear strength was in the order: MP = Chisel = NTnm > Pasture = DiskM > NTm > Forest. Manured treatments (NTm and DiskM) had the lowest CI and shear strength in the cultivated watersheds. The CI (0.64 MPa) and shear strength (24.2 kPa) in NTnm were about twice as high as in NTm (CI = 0.35 MPa and shear strength = 14.3kPa). The NTm and NTnm are adjacent watersheds under similar soil, tillage, and cropping (continuous corn) system with the exception of manuring. Thus,

Table 5. Soil organic carbon (SOC), bulk density  $(\rho_b)$ , cone index (CI), shear strength (SHEAR), and volumetric moisture content  $(\theta_v)$  by soil depth as a function of chisel plow, disk with beef cattle manure (DiskM), no-till with beef cattle manure (NTnm), no-till with no beef cattle manure (NTnm), pasture, and forest management practices at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Management		SOC	SOC pool	$ ho_{ m b}$	CI	SHEAR	$\boldsymbol{\theta}_{\mathbf{v}}$
		$\mathbf{g} \ \mathbf{k} \mathbf{g}^{-1}$	Mg ha <sup>-1</sup>	$Mg m^{-3}$	MPa	kPa	mm³ mm <sup>-3</sup>
			0-10 cm				
MP		13.61	19.56	1.44	0.67	25.52	0.39
Chisel		13.92	19.38	1.39	0.56	25.53	0.37
DiskM		23.72	31.50	1.32	0.29	20.83	0.45
NTm		49.91	54.16	1.09	0.35	14.34	0.47
NTnm		30.03	36.13	1.21	0.64	24.19	0.46
Pasture		25.82	30.28	1.16	0.41	21.61	0.46
Forest		62.73	58.89	0.93	0.19	6.11	0.39
	LSD(0.05)†	0.48	7.68	0.12	0.08	3.55	0.04
			<u>10–20 cm</u>				
MP		12.80	18.63	1.45	0.63	27.00	0.39
Chisel		11.71	16.07	1.37	0.67	28.33	0.35
DiskM		14.79	22.00	1.49	0.53	27.22	0.38
NTm		28.89	38.65	1.34	0.80	23,22	0.38
NTnm		8.14	12.74	1.56	1.39	44.68	0.34
Pasture		13.82	19.98	1.45	0.82	29.22	0.36
Forest		23.78	29.45	1.23	0.38	13.44	0.32
	LSD(0.05)	0.17	2,92	0.08	0.21	6.43	0.04
			20-30 cm				
MP		8.30	12.66	1.53	0.64	20.57	0.38
Chisel		10.31	14.93	1.46	0.87	33.55	0.34
DiskM		9.30	14.42	1.55	0.96	40.17	0.36
NTm		12.52	18.37	1.49	1.39	37.24	0.33
NTnm		6.00	8.99	1.51	1.46	52.80	0.35
Pasture		9.90	14.28	1.44	1.20	41,22	0.39
Forest		15.14	21,21	1.41	0.73	25.78	0.32
	LSD(0.05)	0.24	3.14	0.09	0.23	6.30	0.05

<sup>†</sup> LSD = Least significance difference at the 0.05 probability level.

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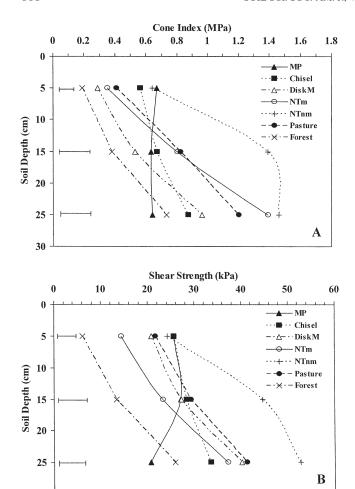


Fig. 1. (A) Cone index and (B) shear strength as a function of depth and management at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio. Error bars represent one standard deviation.

manuring is most likely the primary factor responsible for the reduction of CI and shear strength in NTm. Mosaddeghi et al. (2000) also observed that addition of cattle manure reduced CI in a silty clay loam soil. Soane (1990) stated that manure reduces soil strength by improving soil structure, enhancing biological activity, and promoting formation of macropores. The same author added that manure has elastic properties to buffer against the soil compaction processes.

The lack of differences in CI and shear strength between NTnm and MP implies that significant reconsolidation of MP soils occurred almost a year after the annual tillage. The loose structure of MP soils after plowing is often highly unstable and subsides rapidly, thereby changing the soil strength (Or and Ghezzehei, 2002). Post-tillage soil strength is sensitive to internal capillary forces, wetting and drying, and surface crusting and sealing in concomitance with raindrop impact. Initial soil strength in NT soils often increases rapidly following conversion of MP into NT, but differences diminish with long-term management as the system equilibrates (Katsvairo et al., 2002). Wilkins et al. (2002) reported that NT had higher soil strength than MP, 1 yr after conversion from MP to NT; but strength differ-

ences, 17 yr after conversion to NT, were not significant. Present results differ from those by Hill (1990) and Stelluti et al. (1998), who reported that soil strength in NT is higher than in MP soils. Site-specific factors including duration of tillage, climate, and soil may explain the conflicting results in soil strength behavior.

At 10- to 20-cm depth, forest soil had the lowest CI (0.38 MPa) and shear strength (13.44 kPa), and NTnm had the highest CI (1.39 MPa) and shear strength (44.68 kPa). The CI (0.63 MPa) in MP in the 10- to 20-cm depth was similar to that in the 0- to 10-cm depth (0.67 MPa), which is because of the mixing effect within the plow layer. At the 20- to 30-cm depth, MP had the lowest CI and shear strength in contrast with the upper two depths. Inversion tillage in MP may have reduced soil consolidation at this depth, thereby lowering the CI and shear strength. The NTnm had the highest CI and shear strength at the 20- to 30-cm depth followed by NTm, which indicates that subsoil in NT can be more compacted than that in tilled soils.

In general, shear strength increased with depth except in MP (Fig. 1). The CI in MP decreased slightly with depth from 0.67 to 0.64 MPa, and shear strength decreased from 25.5 to 20.6 kPa. This slight decrease of soil strength may be due to differential soil consolidation in MP soils. Similar results were reported by Hill (1990) for a Bertie silt loam. Increase in CI and shear strength with depth in chisel treatment was also small, indicating that chiseling affected soil strength similar to the MP. Overall, manuring reduces significantly soil strength in the NTm management watersheds. High strength in MP and NTnm may not significantly restrict the plant growth because the CI is below the crop limiting threshold values of 1.5 MPa for medium textured soils (Cassel et al., 1995; Vetsch and Randall, 2002).

### **Bulk Density and Volumetric Moisture Content**

Land use and management affected  $\rho_b$  significantly (P < 0.05; Table 5). Forest had the lowest  $\rho_b$  (0.93 Mg  $m^{-3}$ ), whereas MP had the highest  $\rho_b$  (1.44 Mg  $m^{-3}$ ) for the 0- to 10-cm depth. The  $\rho_b$  for NTm, NTnm, and pasture was significantly lower than that for chisel and MP treatments (P < 0.05; Table 5). The results of lower ρ<sub>b</sub> in NTm and NTnm than MP soils differ from those reported by Hill (1990) and Hussain et al. (1998), who observed higher  $\rho_b$  in NT than in MP in a Bertie silt loam and a Grantsburg silt loam, respectively. However, similar results were reported by Lal et al. (1994) and Kettler et al. (2000), who observed significantly lower  $\rho_b$  in NT than that in plowed systems in a Wooster silt loam and Alliance silt loam. The lower  $\rho_b$  in NT may be explained by the greater earthworm (Lumbricus terrestris L.) population in NT than in MP soils. Indeed, long-term NT soils have more earthworms and continuous macropores (ranging from 0.1 to 1.2 cm diam.) than tilled soils (Butt et al., 1999). Numerous earthworms and wormholes were observed in the soil cores during sampling. The higher  $\rho_b$  in MP is also due to the rapid consolidation accentuated by raindrop impact. Mean ph for the 0- to 10-cm depth of DiskM treatment was similar

to that of NTm, probably because of the manuring. Similar effect of manuring occurred between NTm and NTnm treatments, where NTm (1.09 Mg m<sup>-3</sup>) had lower  $\rho_b$  than NTnm (1.21 Mg m<sup>-3</sup>). Soane (1990) and Schjønning et al. (1994) also reported reduction in  $\rho_b$  in manured compared to non-manured plots.

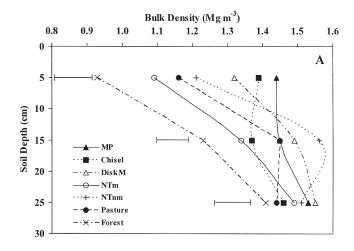
At the 10- to 20-cm depth, NTnm had the highest  $\rho_b$ , and forest the lowest. The high  $\rho_b$  in NTnm at this depth agrees with the high CI and shear strength, suggesting increased soil compaction compared with other treatments. Manured NT soil had significantly lower  $\rho_b$  (1.34 Mg m<sup>-3</sup>) than MP (1.45 Mg m<sup>-3</sup>) at the 10- to 20-cm depth, but not at the 20- to 30-cm depth. Differences in  $\rho_b$  among treatments narrowed considerably with depth (Fig. 2). The  $\rho_b$  values in chisel and MP did not increase sharply with depth as in the other treatments in accord with CI and shear strength.

Soil moisture content was measured only once between 15 and 17 Mar. 2004. Thus, effects of management on  $\theta_{\nu}$  cannot be conclusively stated. Results at the time of measurement showed, however, that management treatments had a significant impact on  $\theta_{\nu}$ . The NTm, NTnm, pasture, and DiskM had significantly higher  $\theta_{\nu}$  than forest, chisel, and MP treatments in the 0- to 10-cm depth, but not at lower depths. Reduced evaporation in NTm and NTnm due to residue cover may explain the higher  $\theta_{\nu}$ . Manuring may be the reason for the high  $\theta_{\nu}$  in DiskM compared with that in chisel and MP treatments. Miller et al. (2002) also reported that  $\theta_{\nu}$  increased linearly with increasing rates of application of beef cattle manure in a clay loam soil.

### **Soil Organic Carbon Concentration**

Effect of land use and management practices on SOC concentration was significant at all depths (Table 5). However, differences in SOC concentration were larger at the 0- to 10-cm depth than at lower depths (Fig. 2). The SOC concentration generally decreased with depth, but the decrease in MP and chisel was less pronounced than in other treatments in accord with those of CI and shear strength. At the 0- to 10-cm depth, the SOC concentration was in this order: Forest > NTm > NTnm > Pasture = DiskM > Chisel = MP. The SOC concentration in forest was 4.6 times higher than that in MP and chisel (P < 0.01). The NTm had the highest SOC concentration of all cultivated watersheds and was 3.6 times higher than that in MP or chisel, and almost twice as much as that in NTnm. The DiskM had 1.7 times higher SOC concentration than chisel and MP probably because of manuring. Motta et al. (2002) reported that SOC concentration in disked soils was less than half of that in NT after 17-yr of tillage system. In the present study, the DiskM was fertilized every third year, during the corn phase of the rotation, and it was manured in 2003, 1 yr before this study.

At the 10- to 20-cm depth, NTm had the highest SOC concentration (28.9 g kg<sup>-1</sup>), and NTnm the least (8.15 g kg<sup>-1</sup>; P < 0.05). The SOC concentration in chisel and MP was 1.5 times higher than that in NTnm treatment (P < 0.05). The sharp decrease in SOC concentration



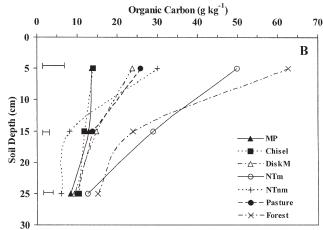


Fig. 2. (A) Bulk density and (B) soil organic C as a function of depth and management at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio. Error bars represent one standard deviation.

in NTnm (from 30.0 g kg<sup>-1</sup> in the 0- to 10-cm depth to 8.15 g kg<sup>-1</sup> in the 10- to 20-cm depth) supports the findings of Yang and Wander (1999), who showed that SOC concentration in NT soils was higher in the 0- to 5-cm depth, equal in the 5- to 15-cm depth, and lower in the 15- to 20-cm depth compared with tilled soils. The SOC concentration in forest also decreased sharply with depth (from  $62.7 \text{ g kg}^{-1}$  in the 0- to 10-cm to 23.8 g $kg^{-1}$  in the 10- to 20-cm depth), which indicates that SOC in forest soils is mostly concentrated near the soil surface in accord with Vesterdal et al. (2002). At the 20- to 30-cm depth, forest  $(15.1 \text{ g kg}^{-1})$  and NTm (12.5 g)kg<sup>-1</sup>) had higher SOC concentration than chisel, pasture, disk manure, and MP treatments (approximately 9.0 g kg<sup>-1</sup>), while NTnm had the lowest SOC concentration (6.0 g kg<sup>-1</sup>; P < 0.05).

The NTm had significantly higher SOC concentration than NTnm at all depths. Manuring combined with NT practice increased SOC concentration by 1.7 times at the 0- to 10-cm depth, 3.5 times at the 10- to 20-cm depth, and two times at the 20- to 30-cm depth compared with the NTnm treatment. These results are similar to those by Mosaddeghi et al. (2000), who observed that SOC concentration increased three times with the ap-

Table 6. Correlation among soil properties across management practices at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.†

	SOC concentration	$ ho_{\rm b}$	$\theta_{\rm v}$	CI	Shear strength
SOC concentration	1.0				
$ ho_{ m b}$	-0.827**	1.0			
$\hat{\boldsymbol{\theta}}_{\mathrm{v}}$	0.392**	-0.437**	1.0		
CI	-0.601**	0.609**	-0.400**	1.0	
Shear strength	-0.708**	0.653**	-0.253**	0.848**	1.0

<sup>\*\*</sup> Significant at the 0.01 probability level.

plication of cattle manure at 50 Mg ha<sup>-1</sup> and 6.5 times with 100 Mg ha<sup>-1</sup> of manure as compared with nonmanured fields. Hao et al. (2003) also reported that application of cattle manure increased SOC concentration significantly in the 0- to 30-cm depth. Increase in SOC concentration with NT practices was confined to the upper 10 cm of soil surface when compared with tilled soils, except when NT was combined with manuring (Fig. 2). Total SOC concentration in NTnm below the 10-cm depth was lower than that in tilled systems. Similar results were observed by Yang and Wander (1999). In general, NT alone increased SOC concentration in the soil surface, but manuring improved further the ability of NT to increase the SOC concentration. These results imply that the effects of NT and manuring on increasing SOC concentration are additive (Mikha and Rice, 2004). While uncontrolled manure application may have detrimental environmental impacts, optimization of manure applications, as recommended by Varel et al. (1999) and Webb et al. (2001), can be a potential means for increasing storage and sequestration of SOC in no-till soils.

# Soil Strength and Organic Carbon Interrelationships

Correlation coefficients among soil properties were highly significant (n=171; P<0.01; Table 6). The SOC concentration was negatively correlated with  $\rho_b$ , CI, and shear strength and positively with  $\theta_v$ . The CI and shear strength values increased with increasing  $\rho_b$ , whereas they decreased with increasing  $\theta_v$ . The CI was highly correlated with shear strength. The correlation between CI and  $\rho_b$  was higher than that reported by Grunwald et al. (2001), implying that CI vs.  $\rho_b$  relationships can be sitespecific (Aase et al., 2001).

Table 7. Relationships between soil organic C and soil strength parameters for the management practices at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Management†	Predictive model	r <sup>2</sup>
DiskM	CI = 1.25 - 0.41OC	0.70**
	SHEAR = 48.56 - 12.02OC	0.79**
NTm	CI = 1.64 - 0.26OC	0.88**
	SHEAR = 41.56 - 5.46OC	0.74**
NTnm	CI = 1.60 - 0.30OC	0.71**
	SHEAR = 54.81 - 9.69OC	0.66**
Pasture	CI = 1.47 - 0.40OC	0.53**
	SHEAR = 48.59 - 10.83OC	0.65**
Forest	CI = 0.74 - 0.10OC	0.55**
	SHEAR = 26.55 - 3.38OC	0.63**

<sup>\*\*</sup> Significant at the 0.01 probability level.

Based on the correlation analysis, PTFs relating CI and shear strength with SOC concentration were computed for each treatment (n = 27) using the point regression method (Tietje and Tapkenhinrichs, 1993). The SOC concentration was an important determinant of soil strength (P < 0.01; Table 7). The regression functions explained between 53 and 88% of variability of SOC concentration vs. soil strength except in MP and chisel treatments. Kay et al. (1997) also reported that CI was very sensitive to changes in SOC concentration, decreasing with increasing SOC concentration. The lack of a functional relationship between soil strength and SOC concentration in MP and chisel treatments ( $r^2 < 0.04$ ) may be due to plowing that reduced changes in soil strength and SOC concentration (Fig. 1 and 2). The effect of SOC concentration on strength properties is thus management dependent.

The relationship between SOC concentration and soil strength for all data points (n=171) across seven watersheds is shown on Fig. 3. A power function provided the best fit of the data and explained 54% of the variability of CI vs. SOC concentration, and 63% of the variability of shear strength vs. SOC concentration. Both functions were significant, thereby indicating that soil strength is a function of SOC concentration (P < 0.01). The decline in soil strength with increase in SOC is up to about 20 g kg<sup>-1</sup> of SOC concentration, followed by a lower rate of decrease between 20 and 70 g kg<sup>-1</sup> of SOC concentration (Fig. 3). Small changes at lower SOC concentration appear to have a large effect in reducing the soil strength (Soane, 1990).

Soil  $\rho_b$  was significantly related to SOC concentration, CI, and shear strength (n=57; Fig. 4). The  $\rho_b$  was more linearly related to SOC concentration in the 0- to 10-cm depth ( $r^2=0.62;$  P<0.01) than in the 10- to 20-cm depth ( $r^2=0.35;$  P<0.05). A quadratic function showed that CI explained 39% of variability in  $\rho_b$  at the 0- to 10-cm depth. A power function explained 60 and 48% of variability between  $\rho_b$  and shear strength at the 0- to 10- and the 10- to 20-cm depths, respectively. Cone index and shear strength increased with increasing  $\rho_b$  particularly in the 0- to 10-cm depth. Results also show that  $\rho_b$  decreased with increasing SOC concentration. The SOC reduces soil strength and  $\rho_b$  by cushioning the soil matrix and improving bonds among and within soil aggregates (Soane, 1990; Kay, 1998).

The PTFs using  $\rho_b$ ,  $\theta_v$ , and SOC as independent input parameters for estimating CI and shear strength for all the data points (n = 171) across treatments, positions, and depths showed that the  $\rho_b$ ,  $\theta_v$ , and SOC explained 42%

<sup>†</sup> SOC, soil organic C;  $\rho_b$ , bulk density;  $\theta_v$ , volumetric water content; CI, cone index.

<sup>†</sup> DiskM, disk with beef cattle manure; NTm, no-till with beef cattle manure; NTnm, no-till with no beef cattle manure.

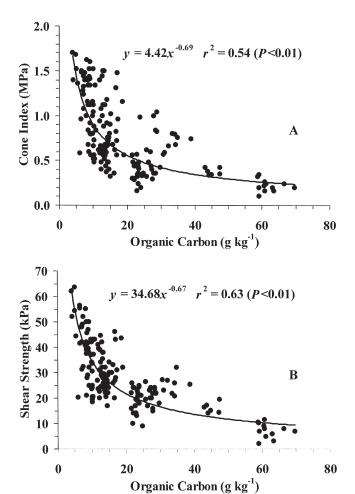


Fig. 3. (A) Cone index and (B) shear strength as a function of soil organic C across treatments, landscape positions, and depths at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

of the variability of CI, while the  $\rho_b$  and SOC explained 52% of the variability in shear strength (Table 8), and both PTFs were significant (P < 0.01). Both  $\rho_b$  and SOC concentration were strong predictors of CI and shear strength. Further study of the PTFs for each treatment showed that the predictive ability of the  $\rho_b$ ,  $\theta_\nu$ , and SOC varied with treatment (Table 8). The PTFs by treatment explained between 55 and 88% of the variation in soil strength in all but the chisel treatment (<44%). Yet, all the soil strength functions were significant. No significant PTFs based on  $\rho_b$ ,  $\theta_\nu$ , and SOC were found for the MP treatment. The SOC was an important determinant of soil strength in DiskM, NTm, pasture, and forest but not in chisel and NTnm.

These results emphasize that the high SOC concentration reduced significantly the soil strength relative to MP and chisel treatments, which had low SOC concentrations. Results are in accord with those reported by Smith et al. (1997), who reported strong dependence of soil strength,  $\rho_b$ , and  $\theta_v$  on SOC concentration. The  $\rho_b$  was an essential determinant of CI only in DiskM, but it was an important predictor of shear strength in chisel, NTm, and forest. The predictive capacity of  $\rho_b$  in soil strength functions is influenced by the level of  $\theta_v$  (Kay

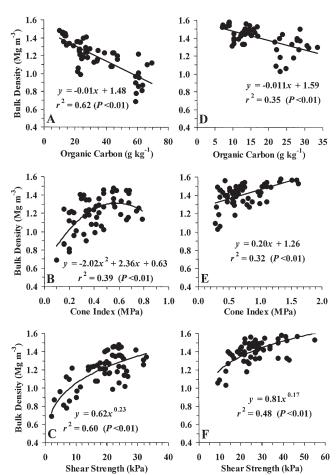


Fig. 4. Bulk density as a function of (A and D) soil organic C, (B and E) cone index, and (C and F) shear strength for the 0- to 10- and 10- to 20-cm depths, respectively, at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

et al., 1997). The predictive power of  $\theta_v$  varied among treatments. The  $\theta_v$  was not present in the PTFs for DiskM, NTm, and forest treatments. Together,  $\rho_b$ ,  $\theta_v$ , and SOC were important variables to predict CI and shear strength but the predictive power of each variable depended on soil management.

Table 8. Pedotransfer functions for predicting cone index (CI) and shear strength for each management practice at the Northern Appalachian Experimental Watershed in Coshocton Co., Ohio.

Management†	Predictive model	$r^2$
Chisel	$CI = 1.96 - 3.56\theta_{v}$	0.30*
	SHEAR = $81.8 - 42.09\rho_d - 141.85\theta_v$	0.44**
DiskM	$CI = 1.70 - 0.03OC - 1.47\rho_d$	0.73**
	SHEAR = 48.58 - 1.20OC	0.79**
NTm	CI = 1.64 - 0.03OC	0.88**
	SHEAR = $90.46 - 29.72\rho_d - 0.87OC$	0.79**
NTnm	$CI = 3.57 - 6.27\theta_{v}$	0.86**
	$SHEAR = 116.39 - 197.640_{v}$	0.75**
Pasture	CI = 2.12 - 0.03OC - 1.810	0.64**
	SHEAR = 48.56 - 1.08OC	0.65**
Forest	CI = 0.74 - 0.01OC	0.55**
	SHEAR = $5.34 + 14.16\rho_d - 0.210C$	0.70**
All treatments	$CI = 0.39 + 0.66\rho_d - 0.01OC - 0.98\theta_v$	0.42**
	SHEAR = $17.37 + 14.32\rho_d - 0.44OC$	0.52**

<sup>\*</sup> Significant at the 0.05 probability level.

<sup>\*\*</sup> Significant at the 0.01 probability level.

<sup>†</sup> DiskM, disk with beef cattle manure; NTm, no-till with beef cattle manure; NTnm, no-till with no beef cattle manure.

### **CONCLUSIONS**

Long-term management practices influenced soil strength and SOC concentration in soils of the North Appalachian region in Ohio. Generally, forest soils had lower strength and higher SOC concentration than pasture and cultivated soils. No-till combined with manuring is the most favorable tillage management for reducing soil strength and increasing both SOC concentration and soil moisture content relative to moldboard systems. Use of organic amendment with cattle manure reduces soil strength properties and increase SOC concentration, particularly in no-till soils. Contrary to most studies, long-term NT may not always lead to increased  $\rho_b$  as compared with tilled management in these soils, which is explained by the abundant earthworm burrows in conjunction with surface residues. The SOC concentration decreases soil strength parameters and increases moisture content, and thus soil strength properties can be estimated using SOC concentration, bulk density, and moisture content as input parameters. While differences among treatments may be confounded by the differences between watersheds because of the lack of "true" field replication, differences among treatments were large and significant.

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