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Indicators of good soil physical quality: density and storage parameters

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Abstract

Optimal values of soil physical quality (SPQ) parameters for enhancing field-crop productivity while maintaining or improving environmental health are still largely unknown. We hypothesized that progress toward identifying optimal values for some SPQ parameters might be made by comparing parameters obtained from long-term conventional tillage cropping (CT), long-term no-tillage cropping (NT), and virgin woodlot (WL) treatments located on Fox sand (Psammentic Hapludalf), Guelph loam (Mollie Hapludalf), and Brookston clay loam (Typic Argiaquoll) soils. Undisturbed 100-mm diameter soil cores were collected from the 0-100-mm depth range and the SPQ parameters, organic carbon (OC), bulk density (BD), porosity (POR), air capacity (AC), field capacity (FC), permanent wilting point (PWP), and plant-available water capacity (PAWC) were determined using standard laboratory methods. Regardless of soil type, OC, POR, and AC were smaller by 12-74% under NT and CT relative to WL, while BD was greater by 28-56%. The FC, PWP, and PAWC parameters showed no consistent differences among WL, CT, and NT. There was no clear advantage of NT over CT or vice versa with respect to any of the parameters measured. The SPQ indicator parameters, OC, BD, AC, and PAWC, all fell within their established "optimum" ranges or limits for the WL management on the loam and clay loam soils. However, these parameters fell outside their optimum ranges for the NT and CT managements on these soils, as well as for all three managements on the sandy soil. The recently proposed guidelines,

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FC/ POR= 0.66 and AC/POR= 0.34, for "ideal" storage capacity of soil water and soil air appear to be useful as additional indicators of good SPQ, given that they yield results consistent with existing guidelines, and they incorporate aspects of soil quality that are not included in other indicator parameters.

Keywords: Soil physical quality; Land management; Conventional tillage; No-tillage; Virgin soil; Soil physical quality indicators

1. Introduction

The physical quality of agricultural soil refers primarily to the soil's strength and fluid transmission and storage characteristics in the crop root zone (Topp *et al.*, 1997). An agricultural soil with "good physical quality" is one that is "strong" enough to maintain good structure, hold crops upright, and resist erosion and compaction; but also "weak" enough to allow unrestricted root growth and proliferation of soil flora and fauna. Soil with good physical quality also has fluid transmission and storage characteristics that permit the correct proportions of water, dissolved nutrients, and air for both maximum crop performance and minimum environmental degradation (Topp *et al.*, 1997).

Intensive field-crop production can cause the physical quality of agricultural soils to decline. Reduced soil physical quality is, in turn, linked to declining crop performance and/or profitability, as well as negative environmental impacts related to the off-field movement of soil (wind/water erosion) and agrochemicals (pesticide/nutrient leaching into surface and ground waters) (e.g. Wallace and Terry, 1998). Progress in the development of practicable new strategies for maintaining or improving the physical quality of intensively cropped soils has been difficult and slow, however, because of complex interactions among tillage practices, soil texture, crop types, and climate (Wallace and Terry, 1998). In addition, "optimal" soil physical quality parameter values for maximum field-crop production with minimum environmental degradation are still largely unknown (Wallace and Terry, 1998; Schipper and Sparling, 2000), although various empirical "guideline" parameter values have been proposed for improved plant growth in agricultural and nonagricultural soils. The most important of these guideline values/criteria are reviewed below.

Using published and unpublished data from 10 studies, Jones (1983) developed empirical regression relationships (his Fig. 2) to distinguish for various soil textures a "lower" critical bulk density below which root growth is effectively unimpeded, and an "upper" critical bulk density above which root growth is severely impeded (upper critical bulk density defined as $\leq$20% of the root growth at the lower critical bulk density). The lower critical density was found to range from about 1.2 to 1.6 Mg m^{-3} for soil silt+ clay contents ranging from 90% to 10%, respectively, while the upper critical densities ranged from about 1.4 to 1.8 Mg m^{-3}, respectively. Comparable upper critical limits were proposed by Veihmeyer and Hendrickson (1948), who found that root extension in clayey soils could stop completely at bulk densities $\geq$1.5-1.6 Mg m^{-3}, and in loamy and sandy soils at densities ≥1.6-1.8 Mg m^{-3}. The recommended bulk densities for constructed urban landscaping soils, on the other hand, range within 1.1-1.4 Mg m^{-3}, depending on the texture of the mineral component the type and amount of amendments added, and the intended land use (Craul, 1999, p: 125).

Good root growth and function requires adequate soil air and soil water storage capacities, in addition to appropriate soil strength or density. Substantial work over the last 30 years suggests that near-surface air-filled soil pore space (i.e. air capacity) should be at least 0.10-0.15 m^3 m^{-3} (Grable and Siemer, 1968; Cockroft and Olsson, 1997). It has also been proposed that plant-available water capacity should be > 0.20 m^3 m^{-3} (Cockroft and Olsson, 1997), or within the range 0.15-0.25 m^3 m^{-3} (Craul, 1999, p. 125).

The "nonlimiting" or "least limiting" water range (LLWR) (Letey, 1985; Kay, 1989) was developed as an attempt to combine soil strength, aeration, and plant-available water capacity into one parameter, indicating overall soil physical quality for crop production. In essence, LLWR is the soil water content range within which plant roots are not unduly impeded in their ability to acquire soil water and soil air necessary for plant growth. Generally speaking, the greater the LLWR, the better the soil physical quality for crop production. The upper limit of the LLWR is defined as the lesser of the field capacity water content or the water content yielding the minimum air-filled pore space required for adequate root aeration (e.g. 0.10-0.15 m^3 m^{-3}). The lower limit, on the other hand, is greater of the permanent wilting point water content or the water content at which soil strength substantially impedes root growth (e.g. cone penetration resistance ≥2000 kPa). The LLWR is linked to the parameters mentioned above through air capacity (soil aeration), the generally strong correlation between cone penetration resistance (soil strength) and bulk density, and the fact that field capacity, air capacity, wilting point, bulk density, and penetration resistance are interconnected so that a change in one of these parameters usually results in a corresponding change in one or more of the other parameters. Major limitations of the LLWR include difficulty in in-situ characterization of the dependence of penetration resistance on antecedent soil water content and bulk density, and the apparent insensitivity of cone penetrometer measurements to soil macropores which present little impedance to root growth (da Silva *et al.*, 1994). Another difficulty is that a critical minimum value, and/or optimum range of the LLWR for maximum crop production, has not yet been defined (da Silva *et al.*, 1994). As a result, LLWR has not been used extensively in soil physical quality studies.

Skopp *et al.* (1990) used diffusion models and experimental data to propose that maximum production of crop-available nitrogen by aerobic microbial mineralization of organic matter occurs (regardless of soil type) when approximately 66% of the soil pore space is water-filled, or alternatively, when about 34% of the pore space is air-filled. They found that soil respiration (indicator of microbial production of nitrogen) decreased sharply for both wetter and dryer conditions as a result of reduced availability (through restricted diffusion) of oxygen or substrate, respectively. Using this result and the fact that water-filled and air-filled pore space depends partially on soil physical characteristics, Olness *et al.* (1998) proposed that an optimal

Table 1. Selected soil physical quality and related parameters.

Parameter, symbol, and units	Parameter definition [a]	Soil physical quality property measured	Method used for measurement [b]
Total organic carbon content, OC wt.%)	Amount of carbon in soil derived from organic sources.	Not a true soil physical quality parameter, but affects many aspects of soil physical quality.	Combustion of sieved soil (0-100 mm depth) followed by CO_2 analysis using a Leco Carbon Analyzer.
Bulk density of total soil, BD (Mg m^{-3})	Mass of dry soil solids per unit bulk soil volume.	Index of soil strength. Also used to obtain water/air storage parameters.	Oven drying (105°C) of intact soil cores (100 mm diameter, 0-100-mm depth range).
Porosity of total soil, POR_t (m^3 m^{-3})	POR_t= [1 -(BD/PD)] PD = 2.65 Mg m^{-3}	Total volume of soil pore space including macropores, matrix pores, and occluded pores.	Calculated using BD measurements from intact soil cores.
Porosity of soil macropore domain, POR_p (m^3 m^{-3})	$POR_p = \theta(h=0) - \theta(h=-100\ mm)$	Volume of soil pores with equivalent diameters ≥ 300 gm (soil macropores).	Tension table desorption from intact soil cores (100 mm diameter, 0-100 mm depth).
Porosity of soil matrix domain, POR_m (m^3 m^{-3})	$POR_m = \theta(h = -100\ mm)$	Volume of soil pores with equivalent diameters <300 gm (soil matrix pores).	Tension table desorption from intact soil cores (100 mm diameter, 0-100 mm depth).
Air capacity of total soil, AC_t (m^3 m^{-3})	$AC_t = \theta(h = 0) - \theta(h= -1000\ mm)$	Index of soil aeration on total soil basis.	Tension table desorption from intact soil cores (100 mm diameter, 0-100 mm depth).
Air capacity of soil matrix, AC_m (m^3 m^{-3})	$AC_m = \theta(h = -100\ mm) - \theta(h = -1000\ mm)$	Index of soil aeration in the soil matrix domain.	Tension table desorption from intact soil cores (100 mm diameter, 0-100 mm depth).
Field capacity, FC (m^3 m^{-3})	$FC = \theta(h = -1000\ mm)$	Index of water holding or storage capacity of soil.	Tension table desorption from intact soil cores (100 mm diameter, 0-100 mm depth).
Permanent wilting point, PWP (m^3 m^{-3})	$PWP = \theta(h = -1.5 \times 10^5\ mm)$	Estimate of soil water volume not readily available to crops.	Pressure plate extraction of sieved soil collected from 0-100-mm depth range.
Plant available water capacity, PAWC (m^3 m^{-3})	PAWC = FC - PWP	Soil water readily available for crop growth.	Combination of methods for FC and PWP determination.

[a] $\theta(h)$=*volumetric* soil water content as a function of pore water pressure head, *h.*

[b] Organic carbon content method based on the dry combustion-carbon dioxide evolution technique (e.g. Tiessen and Moir, 1993); bulk density method based on Culley (1993); tension table and pressure plate extraction methods based on Topp *et al.* (1993).

balance between near-surface soil water holding capacity and aeration may be achieved when,

$$FC/POR_t = 0.66 \quad (1)$$

or alternatively when,

$$AC_t/POR_t = 0.34 \quad (2)$$

where, FC is volumetric soil water content at field capacity, AC_t is total soil air capacity, and POR_t is total soil porosity (for detailed definitions see Table 1). The rationale for this criterion is that in rain-fed agriculture, soils with these ratios are likely to have desirable water and air contents (for good microbial production of nitrogen) more frequently and for longer time periods (especially during the critical early growing season) than soils that have larger or smaller ratios. The applicability and usefulness of these ratios as criteria for indicating good soil physical quality have not yet been tested, however.

One step toward establishing optimal or desirable soil physical quality parameter values for field-crop production might be to compare intensively cropped soils that have undergone consistent and long-term agricultural management, to "virgin" soils that have never been cropped or cultivated. Cropped soils that have undergone consistent, long-term management should be stable with respect to their physical quality, as well as relatively free of residual (and potentially confounding) soil quality effects remaining from previous unrelated anthropogenic activities. Comparing cropped soil to virgin soil will allow delineation of the nature and extent of the changes in soil physical quality (i.e. changes in parameter values) that result from annual cropping. Virgin soil will also give an indication of the level of soil physical quality that is sustainable through natural (non-anthropogenic) processes.

Our objectives for three major agricultural soils in Southern Ontario were to (i) measure and compare selected soil physical quality parameters among treatments consisting of never-cultivated or cropped virgin soil, long-term annual no-till cropping, and long-term annual conventional till (moldboard plow) cropping; (ii) determine the near-surface soil physical quality for the three managements using the existing criteria; and (iii) determine if the $FC/POR_t = 0.66$ and $AC_t/POR_t = 0.34$ ratios are potentially useful as additional indicators of good soil physical quality.

2. Materials and methods

2.1. Field sites and experimental design

Three soil types located at three separate field sites were selected to cover a wide range of the root-zone textures and structures commonly found in the major agricultural soils of Southern Ontario, Canada. These included a "structureless", single-grain Fox sand (90% sand, 5% silt, 5% clay; Psammentic Hapludalf) located at Delhi (42°52'N, 80°31'W); a "structured" Guelph loam (36% sand, 48% silt, 16% clay; Mollic Hapludalf) located at Rockwood (43°38'N, 80°11'W); and a "cracking" Brookston clay loam (28% sand, 35% silt, 37% clay; Typic Argiaquoll) located at Woodslee (42 °13'N, 82 °44' W). The land surface slope was 0.1% for the

Fox sand and Brookston clay loam soils, but about 5% for the Guelph loam soil.

Each of the three field sites included areas under long-term annual conventional tillage cropping (CT), long-term annual no-tillage cropping (NT), and virgin woodlot soil which had not been cropped or cultivated within living memory (WL). Conventional tillage consisted of moldboard plowing in the spring (Fox sand, Guelph loam) or fall (Brookston clay loam), with secondary discing and harrowing immediately before planting, but no further tillage or cultivation after planting. No-tillage used standard no-till equipment and procedures, with the only soil disturbance being that caused by the no-till planter. The CT, NT, and WL treatments had been in place for >15, 7, and >50 years, respectively, on the Fox sand; for approximately 17, 9, and >50 years, respectively, on the Guelph loam; and for 14, 14, and >50 years, respectively, on the Brookston clay loam. The NT treatments had been conventionally tilled prior to the establishment of no-tillage. At the Guelph loam site, tillage operations and crop rows were oriented approximately parallel to the land slope.

The cropped plots (NT, CT) on the Fox sand and Guelph loam soils had a maize *(Zea mays* L.)— soybean *(Glycine max* L. Merr.)—winter wheat *(Triticum aestivum* L.) rotation, while those on the Brookston clay loam had a maize-soybean rotation. Standard agronomic practices were used for fertilization and weed control. The WL plots at each site were vegetated to native trees, shrubs, and grasses of the Lake Erie Lowland Ecoregion (Ecological Stratification Working Group, 1995).

At the virtually flat (0.1% slope) Fox sand and Brookston clay loam sites, the two tillage treatments (NT, CT) were arranged in a randomized complete block design with plot replications of four (Fox sand) and two (Brookston clay loam). At the sloping Guelph loam site (5% slope), the NT and CT tillage treatments (each with a plot replication of 2) were randomized along the mid-slope position to avoid potential slope-induced differences in soil texture, organic carbon content, etc. The adjacent WL treatment at each field site had the same plot replications as the corresponding NT and CT tillages, but obviously could not be randomized with the tillage treatments. There was no evidence, however, of spatial or temporal trends in soil properties within the WL treatments at the Fox sand and Brookston clay loam sites; and the WL treatment plots at the Guelph loam site were established at the same mid-slope position as the corresponding NT and CT plots. The plot sizes were 12 x 10 m on the Fox sand, 15 x 15 m on the Guelph loam, and 6 x 35 m on the Brookston clay loam.

2.2. Soil physical quality parameters

The soil physical quality parameters considered are indicators of soil water storage, soil air storage, and impedance to root growth. The water and air storage parameters included porosity (POR), air capacity (AC), field capacity (FC), permanent wilting point (PWP), and plant-available water capacity (PAWC) (Table 1). These particular parameters were selected because they provide direct, quantitative estimates of the ability of a soil to store root-zone water and air necessary for crop growth (as opposed to some other parameters, such as aggregate stability or aggregate size distribution, which provide indirect estimates). Dry bulk density (BD) was used as an indicator of soil resistance to root elongation (e.g. Jones, 1983; Wallace, 1998). Although not itself a soil physical quality parameter, soil organic carbon content (OC) was also measured because it affects virtually all aspects of soil physical quality (e.g. Wallace and Terry, 1998; Christensen and Johnston, 1997; Gregorich *et al.*, 1997), including all of the parameters mentioned above except perhaps PWP.

Porosity and air capacity were determined for both "soil matrix" and "soil macropore" domains, with the boundary between the domains demarked by the pore water pressure head, $h_m = -100$ mm, or an equivalent pore diameter, $d_m = 0.3$ mm, as determined by the capillary rise equation (e.g. Brady, 1974, p. 179). Thus, equivalent pore diameters ≤ 0.3 mm ($h \leq h_m = -100$ mm) comprise the soil matrix domain, while diameters >0 3 mm ($h > -100$ mm) form the macropore domain. Although there is no agreement in the literature regarding the best values for h_m, and d_m (or if it is even appropriate to use h_m and d_m to distinguish macropores from matrix pores; e.g. Perret *et al.*, 1999; Chen *et al.*, 1993), the values selected here (i.e. $h_m = -100$mm, $d_m = 0.3$ mm) have been used before (e.g. Topp *et al.*, 1997, p. 32; Jarvis *et al.*, 2002) and should serve our purposes adequately. We wish to distinguish the two domains because macropores and matrix pores can function very differently in terms of water and air storage characteristics (e.g. Perret *et al.*, 1999; Bouma, 1991), and might therefore yield different parameter values and/or interparameter relationships among the various land managements (CT, NT, WL). Parameter symbols, units, definitions, and other details are listed in Table 1 for convenience and brevity.

2.3. Apparatus and procedures

The various water and air storage parameters, organic carbon content, and soil dry bulk density were obtained from 100-mm diameter by 100-mm-long intact (undisturbed) soil cores collected from the 0-100-mm depth range. This depth range was chosen because it approximates the plow and/or secondary tillage depths in the CT treatments (80-150 mm), and it exerts a strong influence on crop emergence and early growth. The core samples were collected during July and August to allow sufficient time in the NT and CT managements for the establishment of crop roots and dissipation of transient tillage and planting effects. Three to seven core samples were collected in each treatment plot to obtain a total parameter replication of 8-12 for each land management (WL, NT, CT) at each field site. The core samples were random in the WL plots, and taken from random locations in the non-trafficked soybean crop interrows in the NT and CT plots. The various soil quality parameters were determined using standard tension table, pressure plate extractor, and drying oven procedures (Table 1).

2.4. Statistical analyses

Soil quality parameters were compared among land managements (WL, NT, CT) within each field site (Woodslee, Rockwood, Delhi), but not among field sites. Comparisons were not conducted among field sites because of the confounding effects of different soil types (clay loam, loam, sand), different land slopes (0.1%, 5%), and different crop rotations (maize—soybean—winter wheat, maize—soybean). The field sites were also sufficiently distant from each other to have different precipitations, different crop heat units, and different growing degree days.

A randomized complete block design was used to analyze the data, with treatment plot as the experimental units and soil core samples as the subsampling units (cores nested within treatment plots). This approach was considered suitable, even though the WL treatments were not randomized with the corresponding NT and CT treatments, because the soil core samples were collected at random locations within the WL treatments. Statistical calculations and comparisons were conducted using the PROC MIXED procedure of SAS (Littell *et al.*, 1996), which uses mixed models to account for both fixed and random effects. The independent variables in the SAS model statement were land management (WL, NT, CT) and block plot. The experimental error was the random effect term associated with land management by block interaction, and the subsampling error was the variation among soil core samples within treatment plots. The residual maximum likelihood (REML) method was used to estimate the two variance components, and the LSMEANS and CONTRAST procedures were used to identify significant differences ($P < 0.05, 0.10$) among land managements within soil type.

3. Results and discussion

3.1. Organic carbon and bulk density

The soil organic carbon content, OC, in the 0-100-mm depth range was greater (although not always statistically significant) under the woodlot (WL) management than under the long-term no-till (NT) and long-term conventional till (CT) managements (Table 2). This undoubtedly reflects the greater mass of plant roots and biota that exist in humid climates under virgin woodlot soils, relative to annually cropped soils (e.g. Gregorich *et al.*, 1997). The NT and CT managements, on the other hand, were not significantly different from each other within any of the soil types (Table 2), even when differences in soil bulk density were taken into account (Ellert and Bettany, 1995). Although others have found long-term NT to have greater near-surface OC than long-term CT (e.g. Kern and Johnson, 1993; Pierce and Fortin, 1997; Dick *et al.*, 1997; Hansmeyer *et al.*, 1997), lack of significant difference is not uncommon in the cool, humid soils of eastern Canada, especially over the 0-100-mm depth range (Angers *et al.*, 1997). It is also seen that OC under WL management changed from 2.3% in the sand, to 5.2% in the loam, to 6.8% in the clay loam (Table 2). Under the NT and CT managements, on the other hand, OC was only 0.7-0.8% in the sand, and 2.2-2.7% in the clay loam and loam soils (Table 2). It is also interesting to note that the OC levels in the loam and clay loam under WL management are comparable to the 5% level frequently cited as being necessary for successful and sustainable plant growth in "constructed" landscaping soils used in urban lawns, green spaces, playing fields, street curb sides, etc. (Craul, 1999, p. 150).

The soil dry bulk density, BD, follows an approximate reverse pattern to that of OC. For all three soils, BD under the WL management was lower than under the NT and CT managements, and not different between NT and CT, except for the loam soil where NT had a lower BD than CT (Table 2). The lower BD under WL management was probably a direct consequence of the greater OC and less soil disturbance and compaction for that management relative to the NT and CT managements. The lower and upper critical BDs of Jones (1983, his Fig. 2) were 1.26

Table 2. Organic carbon, bulk density, and water/air storage parameters.

Land management	OC (wt.%)	BD (Mg m^{-3})	POR_t (m^3 m^{-3})	POR_p (m^3 m^{-3})	POR_m (m^3 m^{-3})	AC_t (m^3 m^{-3})	AC_m (m^3 m^{-3})	FC (m^3 m^{-3})	PWP (m^3 m^{-3})	PAWC (m^3 m^{-3})
Brookston clay loam										
WL [a]	6.82 a *A* [b]	0.88 b B	0.669 a A	0.066 a A	0.574 a A	0.201 a A	0.136 a A	0.437 a A	0.218 a A	0.225 a A
	(0.11) [c]	(0.05)	(0.021)	(0.005)	(0.008)	(0.008)	(0.004)	(0.010)	(0.006)	(0.019)
NT	2.19 b B	1.33 a A	0.497 b B	0.054 a AB	0.417 c C	0.094 b B	0.040 b B	0.377 b B	0.231 a A	0.145 a B
	(0.11)	(0.05)	(0.021)	(0.005)	(0.008)	(0.008)	(0.004)	(0.010)	(0.006)	(0.019)
CT	2.25 b B	1.37 a A	0.483 b B	0.032 a B	0.465 b B	0.071 b B	0.036 b B	0.429 a A	0.232 a A	0.186 a AB
	(0.11)	(0.05)	(0.021)	(0.005)	(0.009)	(0.007)	(0.004)	(0.010)	(0.006)	(0.019)
Guelph loam										
WL	5.23 a A	1.05 c C	0.605 a A	0.062 a A	0.508 a A	0.175 a A	0.111 a A	0.399 a A	0.182 a A	0.217 a A
	(0.72)	(0.03)	(0.010)	(0.005)	(0.007)	(0.011)	(0.007)	(0.004)	(0.014)	(0.004)
NT	2.73 a AB	1.34 b B	0.495 b B	0.034 b B	0.448 b B	0.098 b B	0.060 b B	0.388 a B	0.162 a AB	0.227 a A
	(0.72)	(0.03)	(0.010)	(0.005)	(0.006)	(0.010)	(0.006)	(0.004)	(0.014)	(0.004)
CT	2.24 a B	1.55 a A	0.413 c C	0.044 b B	0.389 c C	0.115 b B	0.073 b B	0.312 b C	0.111 a B	0.203 b B
	(0.72)	(0.03)	(0.011)	(0.005)	(0.006)	(0.011)	(0.007)	(0.004)	(0.014)	(0.004)
Fox sand										
WL	2.28 a A	1.10 b B	0.585 a A	0.063 a A	0.500 a A	0.367 a A	0.301 a A	0.187 a A	0.042 a A	0.150 a A
	(0.07)	(0.03)	(0.011)	(0.005)	(0.012)	(0.011)	(0.011)	(0.004)	(0.002)	(0.004)
NT	0.77 b B	1.53 a A	0.435 b B	0.044 b B	0.368 b B	0.258 b B	0.217 b B	0.141 b B	0.041 a A	0.098 b B
	(0.07)	(0.03)	(0.011)	(0.005)	(0.011)	(0.012)	(0.011)	(0.004)	(0.002)	(0.004)
CT	0.73 b B	1.52 a A	0.426 b B	0.037 b B	0.371 b B	0.269 b B	0.231 b B	0.138 b B	0.041 a A	0.096 b B
	(0.07)	(0.02)	(0.011)	(0.005)	(0.011)	(0.011)	(0.011)	(0.004)	(0.002)	(0.004)

See Table 1 for parameter definitions.

[a] WL= virgin woodlot soil; NT= long-term no-till cropping; CT= long-term conventional till cropping.

[b] Means within a column and soil type are significantly different at $P< 0.05$ if followed by a different lower case letter, and at $P< 0.10$ if followed by a different upper case letter ($n= 8$-12).

[c] Bracketted values are standard error which can be used to estimate the confidence interval around the corresponding mean.

and 1.52 Mg m $^{-3}$, respectively, for Brookston clay loam; 1.30 and 1.56 Mg m $^{-3}$, respectively, for Guelph loam; and 1.55 and 1.79 Mg m $^{-3}$, respectively, for Fox sand. Hence, density-induced impedance to root growth was minimal under all three managements in the Fox sand, and under the WL management in the Guelph loam and Brookston clay loam. The loam and clay loam soils under NT and CT management, on the other hand, had density-induced impedance to root growth ranging from slight to substantial. As expected, the porosity of the total soil, POR_t, followed the reverse pattern to that of BD (Table 2).

3.2. Water and air storage

Soil macroporosity, POR_p, tended to decrease from WL to NT to CT, although this was not always statistically significant and the pattern was reversed for NT and CT in the loam soil (Table 2). The greater POR_p under the WL management is probably a consequence of generally greater OC, more extensive root mass, and greater number of burrowing organisms relative to NT and CT (Gregorich *et al.*, 1997). The tendency for greater POR_p, under NT relative to CT, probably reflects a generally greater number of cracks, root channels, and wormholes in NT due to lack of soil disturbance. It is also noted that POR_p, under WL management, was of similar magnitude among all three soil types (statistical comparisons were not conducted). This is surprising (and unexplained) because OC and BD change substantially among the three soil types under WL management (Table 2), and because the macrostructure is visibly very different among the soils. The near-surface macrostructure in the "structureless" sand consisted primarily of large intergranular voids; in the "structured" loam, it was a combination of interpedal cracks, burrows, and abandoned root channels; and in the "cracking" clay loam, it was mainly large shrinkage cracks with a few abandoned root channels. Substantial macroporosity is often considered essential in fine-textured soils for adequate infiltration, drainage, and aeration in an otherwise "tight" crop root zone (e.g. Sutton, 1991; Ehlers *et al.*, 1983; Brady, 1974, p. 55). In fine-textured soils with poor structure, existing macropore networks (e.g. cracks, worm holes, abandoned root channels) are often followed by crop roots to obtain better access to water and nutrients stored within the "massive" soil matrix (e.g. Wallace, 1998; Bennie, 1996; Sutton, 1991; Scott *et al.*, 1988; Ehlers *et al.*, 1983). It should also be noted here in passing that POR_p was defined using the saturated volumetric water content, rather than the porosity of the total soil, POR_t. This was done to account for nonsaturating occluded pores, which tend to be nonfunctioning with respect to the storage and transmission of water and air. One consequence of this defmition is that (POR_p + POR_m) is often slightly less than POR_t in Table 1.

The soil matrix porosity, POR_m, was greater under the WL management than under the NT and CT managements for all three soil types (Table 2). As with POR_p, this pattern probably reflects the greater OC, root mass, and biota under the WL management. Significant, but opposing, differences in POR_m, occurred between NT and CT in the loam and clay loam soils, while no differences appeared between NT and CT in the sand. It is also interesting to note the surprisingly large POR_m, value under WL management in the sandy soil (approximately 0.5 m^3 m^{-3}), which appeared to be due largely to intergranular voids and abandoned root channels.

The air capacity of the total soil and soil matrix, AC_t and AC_m, respectively, was found for all three soils to be greater under WL management, and not different between the NT and CT managements (Table 2). Assuming that an air capacity (as defined in Table 1) of 0.10-0.15 m^3 m^{-3} is the minimum for adequate near-surface root aeration (e.g. Topp *et al.*, 1997; Cockroft and Olsson, 1997), then only the sandy soil was well aerated (perhaps even excessively aerated) for all three managements, and for both the total soil and the soil matrix (i.e. AC_t and $AC_m \gg 0.15$ m^3 m^{-3}). The loam and clay loam soils, on the other hand, were well aerated only on a total soil basis ($AC_t > 0.15$ m^3 m^{-3}) under WL management. Under the NT and CT managements (as well as the soil matrix under WL), the loam and clay loam soils were not well aerated, with both AC_t and AC_m falling near or substantially below the 0.10-0.15 m^3 m^{-3} minimum (Table 2). Crop roots under the NT and CT managements at the loam and clay loam sites might consequently experience periodic aeration deficits, especially those within the soil matrix. In addition, these deficits are likely to be particularly severe and frequent under NT and CT at the clay loam site, given that AC_m was only about 0.04 m^3 m^{-3} and distinct gray-brown mottling is common in the soil matrix at depths as shallow as 50 mm.

The "WL effect" observed above for OC, BD, POR_p, POR_m AC_t, and AC_m (i.e. higher or lower parameter values under WL than under NT and CT) effectively disappeared for the field capacity (FC) and permanent wilting point (PWP) water contents. Within each soil, the FC and PWP values under WL management were not different from their corresponding values under one or both of the other managements, except for FC in the sandy soil (Table 2). This relative lack of sensitivity to management at each site is perhaps not surprising. The PWP water content is determined primarily by clay content (e.g. Brady, 1974, p. 196), which would not be greatly affected by the three managements. The FC water content, on the other hand, is determined by a complex interaction of clay content, soil structure, BD, and OC (e.g. Olness *et al.*, 1998, p. 150), and changes in these factors are often partially compensating with respect to their impact on the FC value.

The "WL effect" was also inconsistent for plant-available water capacity (PAWC). The PAWC tended to be greater under WL than under NT and CT in the sand and clay loam soils, but not in the loam (Table 2). Given that PAWC is derived from FC and PWP (Table 1), the likely reasons for lack of consistent pattern among the three managements will be the same as those proposed above for FC and PWP. It is noted that the PAWC values for the loam soil and WL management of the clay loam meet the >0.20 m^3 m^{-3} criterion suggested in Cockroft and Olsson (1997) for optimum root growth and function. These values also fall within the 0.15 m^3 m^{-3} PAWC 0.25 m^3 m^{-3} range often cited as required for sustained plant growth in constructed urban soils (Craul, 1999, p. 125). The PAWC values for NT and CT in the clay loam and for all three managements in the sand, on the other hand, fall below or at the low end of these recommended ranges. It is also interesting to note that the percentage of the soil water holding capacity that is available for plant use (i.e. PAWC/FC) decreases from a high of 70-80% in the sand, to about 55-65% in the loam, to a low of about 40-50% in the clay loam (Table 2). This occurs because PAWC/FC =1 - (PWP/FC), and the PWP/FC ratio increases from sand to loam to clay loam because PWP increases more rapidly with increasing clay content than does FC (Table 2).

3.3. FC/POR, and AC/POR, ratios

Based on Eqs. (1) and (2), near "optimal" FC/POR_t and AC_t/POR_t ratios occurred under the WL management in the loam and clay loam soils, while under the corresponding NT and CT managements, FC/POR_t was greater than optimal and AC_t/POR_t was less than optimal (Table 3). For the sand soil, on the other hand, FC/POR_t was about half the proposed "ideal" value, and AC_t/POR_t was about twice the ideal value for all three managements (Table 3). The WL management in the loam and clay loam soils consequently produced a near "ideal" balance among FC, AC, and POR_t for microbial production of crop-available nitrogen, while the NT and CT managements of these soils, and all three managements of the sand soil, produced nonideal balances. Allowing that an optimal balance among FC, AC, and POR_t for aerobic microbial activity constitutes better soil physical quality than a nonoptimal balance, then these results compare well with the other criteria used to indicate good soil physical quality. That is, the WL managements on the loam and clay loam were the only treatments where all of the other indicator parameters (i.e. OC, BD, AC, and PAWC) also fell within their respective ideal/preferred ranges. In addition, these ratios provide a criterion that includes additional soil physical parameters (FC, POR_t) and an aspect of soil quality (microbial production of crop-available nitrogen) which are not explicit in the other criteria. The $FC/POR_t = 0.66$ and $AC_t/POR_t = 0.34$ ratios thus appear to be useful as indicators of good soil physical quality.

Table 3. Field capacity (FC) and total soil air capacity (AC_t) as ratios of total soil porosity (POR_t).

Land management	FC/POR,	AC,/POR,
Brookston clay loam		
WL [a]	0.65 a B[b] (0.044)[c]	0.30 a A (0.012)
NT	0.76 a AB (0.043)	0.19 b B (0.012)
CT	0.89 a A (0.044)	0.15 c C (0.012)
Guelph loam		
WL	0.66 b B (0.017)	0.29 a A (0.019)
NT	0.79 a A (0.017)	0.20 b B (0.018)
CT	0.76 a A (0.018)	0.27 a A (0.020)
Fox sand		
WL	0.33 a A (0.010)	0.65 a A (0.019)
NT	0.33 a A (0.010)	0.61 a A (0.019)
CT	0.32 a A (0.010)	0.63 a A (0.018)
"Optimal" values	0.66	0.34

Note that the FC/POR_t and AC_t/POR_t ratios will not necessarily sum to unity because FC, AC_t, and POR, are all calculated independently.

[a] WL = virgin woodlot soil; NT = long-term no-till cropping; CT= long-term conventional till cropping.

[b] Means within a column and soil type are significantly different at $P< 0.05$ if followed by a different lower case letter, and at $P<0.10$ if followed by a different upper case letter *(n=8-12).*

[c] Bracketted values are standard error which can be used to estimate the confidence interval around the corresponding mean.

3.4. Example application of the FC/POR_t and AC_t/POR_t ratios

For the NT and CT managements in the loam and clay loam soils, the FC/POR_t and AC_t/POR_t ratios (Table 3) suggest that FC is too large and/or POR_t is too small (Table 2). It is also noted, however, that FC changed rather little among the three managements or between the two soil types, and that BD was above optimal while AC was below optimal (Table 2). Given that FC is controlled largely by soil matrix properties (i.e. FC is defined as the water content at $h = -1000$ mm, Table 1), then it would appear that the physical quality of the loam and clay loam under NT and CT might be best improved by increasing POR_t through the creation of additional soil macrostructure. This would increase AC and decrease BD, but leave FC relatively unchanged. To accomplish this, one might employ land management strategies (e.g. crop types/rotations, amendments, conditioners, etc.) that mimic the macrostructure-producing functions of the organic matter and biota under the corresponding WL managements.

In the sandy soil, the FC/POR_t and AC_t/POR_t ratios were virtually the same for all three managements, despite the fact that OC and POR_t were substantially greater under WL management than under NT and CT management (Table 2). In addition, the FC/POR_t ratios were about half the optimal value (Eq. (1)), the AC_t/POR_t ratios were about twice optimal (Eq. (2)), the PAWCs were below ideal, and the ACs were excessive (Table 2). The BDs were apparently not restrictive to root growth, however (Table 2). It would thus appear that the physical quality of this soil would be best improved by increasing FC and decreasing AC, while maintaining BD and POR_t relatively unchanged. This would increase the FC/POR_t ratio, decrease the AC_t/POR_t ratio, decrease AC, and increase PAWC. One possible way to achieve this might be to apply polymers and/or fine-grade organic materials to increase the ability of the sandy soil to sorb and retain water (e.g. Al-Omran and Al-Harbi, 1998; Stratton and Recheigl, 1998).

4. Conclusions

Regardless of soil type (sand, loam, clay loam), OC, POR_t, POR_p, POR_m, AC_t and AC_m were consistently smaller (by 12-74%) and BD consistently greater (by 28-56%) under NT and CT managements relative to WL management. The FC, PWP, and PAWC parameters showed no consistent differences among the three managements. Tillage effects (i.e. NT versus CT) were effectively absent in the sandy soil, and inconsistent in the loam and clay loam soils, with respect to the measured soil physical quality parameters. This indicates that there was no general advantage for NT over CT, or vice versa, in the near-surface (0-100 mm depth) physical environments of the three soils.

The WL management in the loam and clay loam soils had the "best" overall soil physical quality in the near-surface (0-100 mm depth) in that the indicator parameters, OC, BD, AC, and PAWC, all fell within their respective optimum/ideal/preferred ranges or limits. The NT and CT managements in the loam and clay loam had less than optimal OC, AC, and PAWC, and greater than optimal BD. In the sandy soil, all three managements produced suboptimal near-surface soil physical quality, as only BD fell within an "ideal" range (Jones, 1983).

The proposed criteria, $FC/POR_t = 0.66$ and $AC_t/POR_t = 0.34$, for "ideal" storage capacity of soil water and soil air appear to be useful as indicators of good soil physical quality. They are consistent with established criteria, such as those used for OC, BD, AC, and PAWC, and they incorporate additional soil physical parameters (FC, POR_t) and other aspects of soil quality (microbial production of nitrogen) which are not explicit in the existing criteria. Further work is required, however, to determine if field-crop productivity and/or rural environmental health will be consistently improved by maintaining these ratios and the other indicator parameters within their respective optimal ranges.

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