Soil & Tillage Research 136 (2014) 61–69

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Effects of compaction and cover crops on soil least limiting water range and air permeability

Guihua Chen *, Ray R. Weil, Robert L. Hill

Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 12 September 2013
Accepted 14 September 2013

Keywords:
Least limiting water range
Air permeability
Brassica cover crop
Compaction

ABSTRACT

Crop rotations that include tap-rooted species of cover crops may help alleviate the deleterious effects of soil compaction on plant growth by modifying soil physical properties. We studied the effects of compaction and cover crops on the least limiting water range (LLWR) and air permeability in the surface layers of a loamy (Exp. 1) and a sandy soil (Exp. 2). There were three compaction treatments [HC (high), MC (medium) and NC (no compaction)] and four cover crop treatments [FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cultivar 'Daikon'), rapeseed (*Brassica napus*, cultivar 'Essex'), rye (cereal rye: *Secale cereale* L., cultivar 'Wheeler') and NCC (no cover crop)]. Rapeseed and FR are tap-rooted species in the Brassica family. Compaction reduced the LLWR in Exp. 1 by decreasing aeration and increasing soil strength and in Exp. 2 by increasing soil strength. Brassica cover crops increased LLWR by reducing the limitations on soil strength. Air permeability at 0–12 cm depth was reduced by compaction in both experiments, and this reduction was associated with pore tortuosity and discontinuity. In Exp. 1, the air permeability under HC following various cover crop treatments was in the order of FR = rapeseed > rye = NCC; under NC condition it was in the order rapeseed = rye > FR > NCC. The overall effect of cover crops in Exp. 1 on air permeability across compaction treatments was in the order of FR = rapeseed > rye = NCC. Cover crops had no affect air permeability in Exp. 2 probably due to the coarse soil texture. The results supported our hypotheses that tap-rooted Brassica cover crops (especially rapeseed) were able to increase LLWR and air permeability, though the magnitude of the increase seemed to be less than the decrease by compaction.

1. Introduction

Soil compaction has become a worldwide problem as a result of intensive cropping, increased use of heavy machinery, short crop rotations and inappropriate soil management practices (Servadio et al., 2001, 2005; Hamza and Anderson, 2005). It is defined as "the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density" (Soil Science Society of America, 1996). The large proportion of reduction in pore space occurs within the macroporosity and the rearrangement of soil aggregates increases the tortuosity of pore conductivity. As a consequence, compaction restricts plant root growth either by increasing mechanical resistance (Hettiaratchi, 1990; Unger and Kaspar, 1994) or by decreasing supply of oxygen (Czyż, 2004), and thereby impedes plant development (Cook et al., 1996) and reduces crop yield (Letey, 1985; Ishaq et al., 2001; Saqib et al., 2004; Vrindts et al., 2005).

Soil strength and aeration are dynamic parameters that are mainly affected by soil structure, texture, and water content. The interactions between water content and bulk density on soil strength and aeration make it difficult to characterize the effects of soil compaction by considering individual soil properties. Letey (1985) proposed the non-limiting water range (NLWR) as a means in which soil water potential, aeration, and mechanical resistance are all taken into consideration as factors indirectly affecting plant growth. This concept was later improved and renamed as the least limiting water range by da Silva et al. (1994). The least limiting water range (LLWR) defined as "the range in soil water within which limitations to plant growth associated with water potential, aeration and mechanical resistance to root penetration are minimal" (da Silva et al., 1994), may provide a better characterization of the effects of compaction on soil physical quality. It integrates the effects of aeration, soil strength and water potential into one index on the basis of soil water content. A wide range of

Abbreviations: LLWR, least limiting water range; PR, penetration resistance; D_b, bulk density; k_a, air permeability; FR, forage radish; HC, MC and NC, high, medium and no compaction, respectively.

* Corresponding author at: 4112 Plant Science Building, The University of Maryland, College Park, MD 20742, USA. Tel.: +1 240 643 3251.
E-mail address: gchen06@gmail.com (G. Chen).

0167-1987/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.still.2013.09.004

LLWR implies that the soil is more resilient to environmental stresses and plants growing in the soil are less likely to suffer from poor aeration, water stress and/or mechanical impedance and the soil is more productive, compared to soil with a narrow range of LLWR (da Silva and Kay, 2004). The application of the LLWR concept has been used to understand the effects of soil properties on nitrogen mineralization (Drury et al., 2003) and crop production (da Silva and Kay, 1996; Lapen et al., 2004; Beutler et al., 2005).

In conservational tillage systems, biological activity is usually observed to modify soil structure associated with biopores and aggregates stability (Stirzaker et al., 1996; Ball et al., 2005), but changes in soil bulk density and penetration resistance may or may not be detected depending on root distribution, plant residues and time scale. Soil air permeability, a parameter that determines the pore geometric effects on gas and liquid transport processes, may be a good indicator for characterizing the changes of soil structure associated with biological activity. Air permeability has been reported to be very sensitive to macro-porosity and pore continuity (Tuli et al., 2005; Cavalieri et al., 2009; Dörner and Horn, 2009) and to be well correlated with saturated hydraulic conductivity (Loll et al., 1999; Chief et al., 2008).

In the Mid-Atlantic region of the USA, conservational tillage and incorporation of fall/winter cover crops are encouraged as effective practices to control soil erosion and reduce post-harvest soil nitrogen leaching to the Chesapeake Bay (Coale et al., 2001; Dean and Weil, 2009). However, compaction remains a constant problem no matter which cropping systems are chosen unless traffic patterns are either altered or eliminated completely (Ball et al., 1997). The humid climate of the region sometimes makes field operations unavoidable during wet conditions and thus, soil compaction can be particularly challenging in this region. Brassica cover crops, newly introduced to Maryland, were found to help alleviate the effects of soil compaction (Williams and Weil, 2004; Chen and Weil, 2011). Their tap roots grow rapidly and deeply in the fall when soil is relatively moist and may be able to penetrate the compacted layers more often than the fibrous-roots of rye, a more commonly grown cover crop in the region (Chen and Weil, 2010). The modification to the soil structure by the Brassica cover crop roots may provide a better soil environment for root growth by broadening the LLWR and increasing air and water conductivity. Our objectives were (1) to quantify the LLWR for soils following different cover crop and compaction treatments; and (2) to compare the effects of the cover crops on soil air permeability in the compacted soils.

2. Materials and methods

2.1. Site and soil description

The study consisted of two experiments located in adjacent fields on the north farm of the USDA-ARS Beltsville Agricultural Research Center in Beltsville, MD, a site in the coastal plain eco-region in Maryland, USA (39°01′ N, 76°55′ W). Prior to our experiments, conventional tillage consisting of moldboard plowing followed by disking was used in both fields. The recent cropping history for the Exp. 1 field was potato (*Solanum tuberosum*) in summer 2005 and rye cover crop planted in fall 2005. Near-term cropping history for Exp. 2 field was green bean (*Phaseolus vulgaris*) in summer 2005, rye cover crop in winter 2005, Zucchini (*Cucurbita pepo*) in summer 2006, and cereal rye planted in fall 2006.

The soils for the Exp. 1 field varied from Elsinboro series (fine-loamy, mixed, semiactive, mesic Typic Hapludults) at the west end to Woodstown series (fine-loamy, mixed, active, mesic Aquic Hapludults) at the east end with 0–5% slope in the east–west direction. The A horizon soils ranged from sandy loam (12.5% clay) to loam (18.2% clay). The soils in the Exp. 2 field varied from Elsinboro series at the southwest side to Galestown series, gravelly variant (siliceous, mesic Psammentic Hapludults) at the southeast side of the field with 0–5% slope in the northwest-southeast direction. The A horizon soils ranged from coarse loamy sand (5.1% clay) to loamy sand (7.7% clay). The high percentage of coarse sands and cobbles in block III of Exp. 2 made it difficult for accurate field measurements, therefore, only data from block I, II and IV of Exp. 2 were used for the analysis.

2.2. Experimental design, treatments and field operations

A randomized complete block design was used for both fields with four blocks in Exp. 1 and three blocks in Exp. 2. Blocks in the experimental design were arranged to help remove the spatial variations in soil texture and slope. Each block in Exp. 1 contained 12 plots and in Exp. 2 nine plots due to the smaller field size. The plot dimensions were 3.0 m × 9.0 m, and 3.3 m × 12.2 m for Exp. 1 and 2, respectively. Blocks in the fields were separated by 10.7 m (Exp. 1) and 12.2 m (Exp. 2) wide alleys for equipment operations during the creation of the compaction treatments and crop planting. Experiment 1 was established in August 2006 and continued until September 2008. Experiment 2 was conducted from August 2007 to September 2008. There were three compaction treatments [HC (high), MC (medium) and NC (no compaction)] and four cover crop treatments [FR (forage radish: *Raphanus sativus* var. *longipinnatus*, cultivar 'Daikon'), rapeseed (*Brassica napus*, cultivar 'Essex'), rye (cereal rye: *Secale cereale* L., cultivar 'Wheeler') and NCC (no cover crop)] used during the study. Rapeseed and FR are tap-rooted species in the Brassica family. In Exp. 1, all compaction levels and four levels of cover crops (FR, rapeseed, rye and NCC) were combined in a factorial arrangement to provide total 12 treatments. Experiment 2 included all the compaction levels but only three cover crop levels (FR, rye and NCC) for a total of nine treatment combinations. Compaction-cover crop treatment combinations are abbreviated as HC-FR, HC-NCC, HC-rapeseed, HC-rye, etc.

Prior to establishment of the compaction treatments, both fields were deep-ripped then moldboard plowed and finally disked to an 8-cm depth. In middle to late August 2006 (Exp. 1) and 2007 (Exp. 2), the fields were irrigated to saturation and then allowed to drain for 2–3 days before compaction was applied. For Exp. 1, a John Deere 544C front-end loader tractor (axle load 11.88 Mg with solid rubber tires and a rear tire contact area of 1652 cm^2) was used to establish the compaction treatments. High compaction consisted of two passes on the entire plot surface area. The second pass was done with the front-end loader bucket full of rocks to give an axle load of 12.91 Mg. Medium compaction was established by one pass of the tractor without rocks in the bucket and the no compaction treatment received no externally applied compaction with the tractor. For Exp. 2, a single pass of the John Deere 544C tractor was used to create the high compaction, a single pass of a John Deere 7220 tractor (axle load 5.83 Mg with pneumatic tires and a rear tire contact area of 1610 cm^2) was used to create the medium compaction, and the no compaction treatment received no externally applied compaction with the tractor. Immediately after the compaction treatments were imposed, the soil in both experiments was disked to an 8-cm depth to establish a suitable seedbed.

Cover crops were seeded in late August of 2006 (Exp. 1) and of 2007 (Exp. 1 and 2) using a no-till drill with a 16-cm row spacing. Cover crop seeding rates were 14, 9 and 134 kg ha^{-1} for FR, rapeseed and rye, respectively. On 22 September, 2006, 28 kg N ha^{-1} as urea ammonium nitrate (UAN) granular was applied because of the observed nitrogen deficiency. To ensure vigorous growth, the cover crops in 2007 in both experiments were planted with 22 kg N ha^{-1} UAN granular as a starter fertilizer. Because of an unusually short dry period that occurred after planting cover crops in 2007, about 30 mm of water was irrigated on 16 October in Exp. 1 and on 5 September and 16 October in Exp. 2.

Forage radish at the vegetative stage was frost-killed during December to January when air temperatures dropped below −4 °C for several nights in a row. Rapeseed and rye cover crops were killed on 11 April 2007 (Exp. 1) and 16 April 2008 (Exp. 1 and 2) using a combination of glyphosate [N-(phosphonomethyl) glycine] (1.85 L ha^{-1} active ingredient (a.i.)) and 2,4-D (2,4-dichlorophenoxyacetic acid) (1.05 L ha^{-1} a.i.). Maize (Zea mays, Pioneer, 34B62, glyphosate tolerant) was planted on 24 April 2007 (Exp. 1) and 5 May 2008 (Exp. 1 and 2) with a no-tillage planter in four 76-cm rows per plot at an average population of 74,000 seeds ha^{-1} with 22 kg N ha^{-1} UAN granular as a starter fertilizer. Weeds in maize were controlled with glyphosate (1.85 L ha^{-1} a.i.) on 9 May 2007 (Exp. 1) and 18 June 2008 (Exp. 1 and 2). On 7 June 2007 (Exp. 1) and 10 June 2008 (Exp. 1 and 2), 112 kg N ha^{-1} as a UAN solution was dribbled on the soil surface between rows. Maize silage in Exp. 1 was harvested on 16 August 2007 and the field was sprayed with glyphosate (1.85 L ha^{-1}) to kill weeds prior to planting the second-year cover crops.

2.3. Soil physical property measurements

Soil penetration resistance, bulk density and moisture were measured in mid-March 2008. A recording cone penetrometer (Spectrum Technologies, Plainfield, IL) was used to measure soil strength. The penetrometer has a 10-mm diameter steel rod with a 25-mm length and 15-mm maximum diameter cone tip integrated with a strain gauge and data logger. At each location, the penetrometer was pushed by hand at a constant rate of 4 cm s^{-1} 1 down to the depth of 20 cm. Mean penetration resistance was recorded in kPa for every 5-cm depth increment to 15 cm. Penetration resistance was measured at 10 randomly selected locations per plot. Concurrent with measuring soil strength, ten undisturbed soil cores per plot were taken to a 20-cm depth with a 1.85-cm diameter JMC soil bulk density probe (JMC Soil Samplers, Newton, IA, USA). All cores were divided into 5-cm increments, weighed, dried and re-weighed to determine soil bulk density and soil moisture content. Data from the 10–15 cm depth increment were used for the analysis of LLWR because that zone was where compaction differentiation remained when the soil was disked to 8 cm after compaction treatments were applied.

The relationship between soil water content and water potential was determined using repacked soil samples. Soils were packed to the mean D_bs of the HC and NC treatments in each experiment. This is because the interaction effect between compaction and cover crop treatments and the cover crop main effect on soil bulk density were not significant ($P \leq 0.05$), while the compaction effect on soil bulk density was significant. Soil samples from the 10–15 cm depths of each block were taken, dried, ground and sieved through a 2-mm sieve. A known weight of soil was packed into a steel ring (76.2-mm inner diameter and depth of 35.8 mm) to achieve the desired bulk densities for HC and NC treatments corresponding to those measured in the fields and replicated three times for each soil texture in Exp. 1 and 2. The soil water retention curve was determined using a tension table and pressure plates following the procedures described by Topp and Zebchuk (1979) and Dane and Hopmans (2002), respectively. Each sample was subjected to the following suctions: 0.001, 0.003, 0.004, 0.006 and 0.007 MPa on the tension table, and positive pressures of 0.02, 0.04, 0.06, 0.08, 0.1, 0.3, 0.5 and 1.5 MPa in the pressure chamber. The soil water release curve was generated for each soil texture in Exp. 1 and 2 using RETC-fit version 6.02 software that applied the van Genuchten–Mualem model (Mualem, 1976; van Genuchten, 1980). The fitted nonlinear equations were used to convert soil water content at known penetration resistances to water tension.

Air permeability was measured in early to middle June 2008 in both experiments. A field air permeameter (Department of Agronomy and Soils, Auburn University, Auburn, AL) based on concepts described by Jalbert and Dane (2003) was used to measure air permeability. A 16-cm long PVC cylinder with an inner diameter of 10.16 cm was inserted into the soil and a cylindrical PVC chamber was used to seal one end. The measurement was taken first with the cylinder inserted to a 3-cm depth. The chamber cover was then removed and the cylinder was pushed further to a 6-cm depth for another measurement. This procedure was repeated for every 3-cm increment until the PVC cylinder reached the 12-cm depth. Tygon tubes connected the two ends from the sealed chamber to the air permeameter. A 9-volt rechargeable battery-powered pump forced a constant low flow of air from one end of the permeameter to the PVC cylinder inserted in the soil, while at the same time the change in air pressure above the soil was detected by the pressure transducer which sent a corresponding voltage signal to a voltmeter integrated with a computer chip to convert the voltage signal to a back-pressure reading in units of cm H_2O at the other end. The air flow meter measured the rate of air flow at any point in time. For each depth, air temperature, back pressure, and air flow rate were recorded. After air permeability was measured at all 4 depths (0–3, 0–6, 0–9 and 0–12 cm), the volumetric soil water content was measured at 1.5, 4.5, 7.5 and 10.5 cm using a horizontally-inserted capacitance soil moisture probe (EC-5, Decagon, Inc.). Measurements were taken at three randomly selected locations per plot in the pre-existing cover crop rows.

Soil bulk densities at 0–3, 0–6, 0–9 and 0–12 cm depths were calculated from the bulk density of the 5 cm increments. Bulk densities at 0–5, 5–10, 10–15 cm depths were labeled as D_{b1}, D_{b2} and D_{b3}, respectively. By using depth as a weighted parameter, a mean weighted soil bulk density was calculated as: $D_{b(0–3\ cm)} = D_{b1}$; $D_{b(0–6\ cm)} = D_{b1} \times (5/6) + D_{b2} \times (1/6)$; $D_{b(0–9\ cm)} = D_{b1} \times (5/9) + D_{b2} \times (4/9)$; and $D_{b(0–12\ cm)} = (D_{b1} + D_{b2}) \times (5/12) + D_{b3} \times (2/12)$. The total porosity at each depth $f = 1 - (D_b/D_p)$; and the air-filled porosity $\varepsilon_a = f - \Theta$ were measured where D_p was the particle density (2.65 g cm^{-3}) and Θ was the measured volumetric water content.

2.4. Theories

2.4.1. Least limiting water range (LLWR)

The LLWR is a type of pedotransfer function which integrates the effects of soil bulk density (D_b), penetration resistance (PR), water content (Θ) and water potential (ψ) into an index to estimate optimal soil water content for a given soil type. The functional relationship of PR, Θ and D_b was fitted for different cover crop treatments in each experiment using the model employed by da Silva et al. (1994).

$$\mathrm{PR} = a\Theta^b D_b^c \tag{1}$$

The functional relationship between Θ and ψ, incorporated with the effect of D_b was fitted using the model employed by Leao et al. (2006).

$$\Theta = \exp(d + eD_b)\psi^f \tag{2}$$

In the above equations, a, b, c, d, e and f are used as either integers or superscripts are the model-fitting parameters.

Plant root growth is usually reported to be reduced by 50% at PR between 2.0 and 3.0 MPa, and generally stops when PR is greater than 3.0 MPa (Bengough and Mullins, 1990). The critical value for PR was chosen as 2.5 MPa. The field capacity and wilting point were established as Θ at matric potentials of -0.01 and -1.5 MPa. Air-filled porosity $\leq 10\%$ was assumed to be the critical value limiting plant growth (da Silva et al., 1994). The water content, at which air-filled porosity was calculated, was defined as:

$$\Theta_{\mathrm{AFP}} = \left[\left(\frac{1-D_{\mathrm{b}}}{D_{\mathrm{p}}}\right) - 0.1\right] \tag{3}$$

where a particle density (D_p) of 2.65 g cm^{-3} was assumed.

The LLWR was then determined for each cover crop treatment per experiment based on the values of the functions Θ_{PR}, Θ_{FC}, Θ_{WP} and Θ_{AFP}. The selection of Θ values to calculate LLWR used the same method employed by Wu et al. (2003).

If $\Theta_{AFP} \geq \Theta_{FC}$ and $\Theta_{PR} \leq \Theta_{WP}$, LLWR = $\Theta_{FC} - \Theta_{WP}$;
If $\Theta_{AFP} \geq \Theta_{FC}$ and $\Theta_{PR} \geq \Theta_{WP}$, LLWR = $\Theta_{FC} - \Theta_{PR}$;
If $\Theta_{AFP} \leq \Theta_{FC}$ and $\Theta_{PR} \leq \Theta_{WP}$, LLWR = $\Theta_{AFP} - \Theta_{WP}$;
If $\Theta_{AFP} \leq \Theta_{FC}$ and $\Theta_{PR} \geq \Theta_{WP}$, LLWR = $\Theta_{AFP} - \Theta_{PR}$.

2.4.2. Soil air permeability

Soil air permeability (k_a) is based on the assumption that Darcy's law is applicable to the air movement in the soil (Liang et al., 1995; Jalbert and Dane, 2003). The equation to calculate the air permeability was based on Darcy's law while taking the geometry of the cylinder into account as employed by Jalbert and Dane (2003).

$$k_{\mathrm{a}} = \frac{\mu}{DG} \times \frac{Q}{\Delta P} \tag{4}$$

where k_a is the air permeability measured in the soil column (μm^2); μ is the air dynamic viscosity (Pa s), dependent on the air temperature; D is the diameter of the PVC cylinder (m); G is the geometric factor (unitless) depending on the diameter of PVC cylinder and depth inserted; Q and ΔP are the flow rate (m^3 s^{-1}) of the air pumped and the pressure difference (Pa) between the air inside the cylinder above the soil and the free atmosphere, respectively. Air dynamic viscosity (μ) was calculated as

$$\mu = (1717 + 4.8T) \times 10^{-8} \tag{5}$$

where T was the air temperature in degree Celsius.

Geometric factor (G) was calculated as proposed by Jalbert and Dane (2003).

$$G = \left[\left(\frac{\pi}{4} + \frac{D}{H}\right) \times \ln\left(\frac{1+D}{H}\right)\right]\left(\frac{1+D}{H}\right) \tag{6}$$

where D was the diameter (m) of the PVC cylinder and H was the depth (m) of the PVC cylinder that was inserted.

Air permeability (k_a) was related to air-filled porosity (ε_a) (m^3 m^{-3}) using an empirical form of the Kozeny–Carman equation presented by Ball et al. (1988) as follows.

$$k_{\mathrm{a}} = M\varepsilon_{\mathrm{a}}^{N}, \tag{7}$$

or

$$\log k_{\mathrm{a}} = \log M + N \log \varepsilon_{\mathrm{a}} \tag{8}$$

where M and N are empirical constants.

2.5. Statistical analysis

The PROC NLIN procedure of SAS (SAS v. 9.1, SAS Institute, Cary, NC), as described by Leao et al. (2005) was performed to estimate the fitting variables a, b and c in the equation of the pedotransfer function for LLWR (da Silva et al., 1994) and variables d, e and f in the equation of the functional relationship for soil water content, water potential and bulk density (Leao et al., 2005). An ANCOVA model in the PROC MIXED procedure of SAS was used to determine if there were significant relationships between air-filled porosity and air permeability. Prior to the analysis by ANCOVA and making mean comparisons, measurements of air permeability (k_a) and air-filled porosity (ε_a) were $\log_{10}$ transformed to meet assumptions of normality. For each depth interval, the full ANCOVA model included compaction and cover crop as fixed factors, log(ε_a) as a covariate, and block as a random factor. Non-significant terms were removed from the full model through an iterative process in which the highest order of non-significant ($P > 0.05$) interactions were removed in each iteration to create a reduced model. When there was a significant interaction between log(ε_a) and compaction, parameters (intercepts and slopes of linear relationships) were compared using estimate statements in SAS. When the F-test for compaction, cover crop effects were significant ($P \leq 0.05$) while for log(ε_a) was insignificant, mean separations were done using PDIFF options of the LSMEANS statement to compare the interaction effects while the SLICE option was also employed to identify the main effects of compaction and/or cover crop treatments.

3. Results

3.1. Least limiting water range

The water content measured at different water tensions for the two soils (sandy loam and loam) at the 10–15 cm depth in Exp. 1 did not vary significantly and the data were thus pooled to generate one retention curve for each compaction treatment in Exp. 1. Table 1 presents the van Genuchten parameters of RETC-fitted water retention curves for soils exposed to HC and NC treatments for each experiment.

Table 2 presents mean soil bulk density, penetration resistance, and water content for each cover crop under three compaction levels at 10–15 cm depth. In both experiments, the cover crop main effect and the cover crop × compaction interaction effect did not significantly affect soil bulk density or penetration resistance. However, compaction had a significant effect on bulk density and penetration resistance in both experiments. In Exp. 1, soil bulk density and penetration resistance were in the order of HC > MC > NC; while in Exp. 2 soil bulk density and penetration resistance were in the order of HC > MC = NC.

Soil water potentials for high and no compaction levels were calculated using water release equations derived from RETC-fit software 6.02. Mean and standard error of soil water potential are also presented in Table 2. Table 3 lists the coefficients from the least-squares fit of the soil penetration resistance curve for each cover crop in the two experiments. For all cover crops except for

Table 1
Soil texture, bulk density (BD), and van Genuchten parameters for soils at high compaction (HC) and no compaction (NC) treatments in Exp. 1 and 2 where θ_s is the saturated water content (cm^3 cm^{-3}) and α and n are empirical shape parameters.

Exp.	Texture	Compaction	Clay (%)	BD (g cm^{-3})	θ_s (cm^3 cm^{-3})	α	n	R^2
1	Sandy loam–loam	HC	12.5–18.0	1.73	0.319	0.038	1.374	0.88
		NC		1.55	0.422	0.135	1.303	0.94
2	Loamy sand	HC	5.1–7.7	1.67	0.404	0.354	1.265	0.97
		NC		1.54	0.422	0.249	1.296	0.98

Table 2
Mean soil bulk density (D_b), penetration resistance (SR), water content (Θ) and water potential (Ψ) (absolute value) for the forage radish (FR), no cover crop (NCC), rapeseed, and rye cover crops under three compaction levels at 10–15 cm depth.

Exp.	Cover crop	Compaction level	D_b (g cm^{-3})		SR (MPa)		Θ (cm^{-3} cm^{-3})		Ψ[a] (MPa)	
			Mean	Std error	Mean	Std error	Mean	Std error	Mean	Std error
1	FR	High	1.73	0.026	2.85	0.311	0.249	0.009	0.008	0.0154
		Medium	1.68	0.027	1.89	0.253	0.265	0.014		
		No	1.57	0.023	1.43	0.117	0.243	0.019	0.031	0.0620
	NCC	High	1.75	0.020	3.17	0.221	0.249	0.026	0.031	0.0614
		Medium	1.64	0.032	2.24	0.203	0.251	0.017		
		No	1.54	0.011	1.29	0.036	0.241	0.019	0.040	0.0808
	Rapeseed	High	1.72	0.030	2.25	0.165	0.252	0.019	0.024	0.0474
		Medium	1.70	0.027	2.14	0.172	0.244	0.015		
		No	1.56	0.039	1.11	0.113	0.244	0.018	0.033	0.0657
	Rye	High	1.74	0.012	2.11	0.199	0.271	0.006	0.004	0.0081
		Medium	1.67	0.035	1.89	0.218	0.262	0.018		
		No	1.53	0.036	1.14	0.162	0.262	0.010	0.008	0.0166
2	FR	High	1.63	0.045	1.92	0.298	0.231	0.022	0.037	0.0178
		Medium	1.55	0.019	1.30	0.131	0.232	0.007		
		No	1.49	0.047	1.47	0.283	0.203	0.032	0.089	0.0435
	NCC	High	1.68	0.049	2.09	0.457	0.255	0.015	0.020	0.0056
		Medium	1.62	0.037	1.18	0.162	0.257	0.010		
		No	1.51	0.052	1.03	0.073	0.207	0.025	0.071	0.0238
	Rye	High	1.70	0.045	1.78	0.167	0.245	0.024	0.029	0.0147
		Medium	1.57	0.012	1.41	0.245	0.246	0.030		
		No	1.55	0.087	1.13	0.047	0.240	0.034	0.051	0.0320

[a] Ψ was calculated using the water release equation derived by RETC-fit version 6.02 software (van Genuchten–Mualem model) for each known soil texture and compaction level.

rye in Exp. 2, soil penetration resistance varied negatively with water content, but positively with bulk density. However, the positive relationship between penetration resistance and water content for the rye treatment in Exp. 1 contradicted the generally held assumption that penetration resistance decreases as water content increases although it should be noted that this relationship for rye in Exp. 2 was not significant. Poor relationships between penetration resistance and bulk density were observed for the rye cover crop in both experiments and might be due to the small variations of soil water content when taking the measurements.

Table 4 lists the coefficients from the least-squares fit of the soil water release curve for each cover crop treatment in the two experiments. Soil water content varied negatively with bulk density and water tension, which is consistent with previous research (Leao et al., 2006).

Fig. 1 presents the variation of soil water content with bulk density at critical levels of field capacity (−0.01 MPa), wilting point (−1.5 MPa), air-filled porosity (10%) and soil resistance (2.5 MPa) at the 10–15 cm depth for FR, NCC, and rapeseed in Exp. 1 and FR and NCC treatments in Exp. 2. The critical bulk density at which LLWR equaled zero was 1.72, 1.70, and 1.77 g cm^{-3} for FR, NCC, and rapeseed treatments in Exp. 1, respectively, and 1.75 and 1.73 g cm^{-3} for FR and NCC treatments in Exp. 2, respectively. The variation of LLWR as a function of bulk density is presented in Fig. 2 for FR, NCC and rapeseed in Exp. 1 and for FR and NCC in Exp. 2.

3.2. Soil air permeability

The ANCOVA for the full model showed that the three way interaction of compaction, cover crop and air-filled porosity was insignificant ($P > 0.05$) in both experiments at all depth intervals. Table 5 presents the *F*-statistical significance for compaction, cover crop and air-filled porosity on air permeability in the reduced model in which the three way interaction was removed. In Exp. 1, there was a significant interaction between compaction and cover crop treatments on air permeability at 0–12 cm depth interval. In Exp. 2, porosity had a significant effect on air permeability at 0–6 and 0–9 cm depth intervals; compaction, interaction effects between compaction and cover and between compaction and porosity were significant at 0–12 cm depth.

Table 6 presents the air permeability ($\log(k_a)$) at 0–12 cm depth for each cover crop and compaction treatment combination in Exp.

Table 3
Coefficients from the least-squares fit of the soil penetration resistance curves for the forage radish (FR), no cover crop (NCC), rapeseed, and rye cover crop treatments in the two experiments where *a*, *b*, and *c* are fitted parameters for the curves.

Cover crop	*a*[a]	*b*[a]	*c*[a]	*P*[b]	R^2 [c]
Exp. 1					
FR	0.026	−0.489	7.220	<0.001	0.84
NCC	0.071	−0.411	5.704	<0.001	0.85
Rapeseed	0.058	−0.708	4.788	0.003	0.60
Rye	0.363	0.619	4.691	0.001	0.72
Exp. 2					
FR	0.0005	−3.041	7.819	<0.001	0.95
NCC	0.00004	−3.674	10.829	<0.001	0.67
Rye	0.102	−0.889	2.904	0.132	0.29

[a] Coefficients estimated for the model.
[b] Values indicate the possibility of a greater *F*-value.
[c] The fraction of the total variance of soil penetration resistance explained by the curve fit model.

Table 4
Coefficients from the least-squares fit of the soil water release curve for the forage radish (FR), no cover crop (NCC), rapeseed, and rye cover crop treatments in the two experiments where *d*, *e*, and *f* are fitted parameters for the curve.

Cover crop	*d*[a]	*e*[a]	*f*[a]	*P*[b]	R^2 [c]
Exp. 1					
FR	−1.627	−0.197	−0.185	<0.001	0.97
NCC	−1.242	−0.366	−0.143	<0.001	0.90
Rapeseed	−1.670	−0.203	−0.201	<0.001	0.97
Rye	−1.559	−0.196	−0.164	<0.001	0.97
Exp. 2					
FR	−1.926	−0.230	−0.238	<0.001	0.98
NCC	−2.007	−0.153	−0.229	<0.001	0.96
Rye	−1.865	−0.294	−0.253	<0.001	0.98

[a] Coefficients estimated for the model.
[b] Values indicate the possibility of a greater *F*-value.
[c] The fraction of the total variance of soil water content explained by the curve fit model.

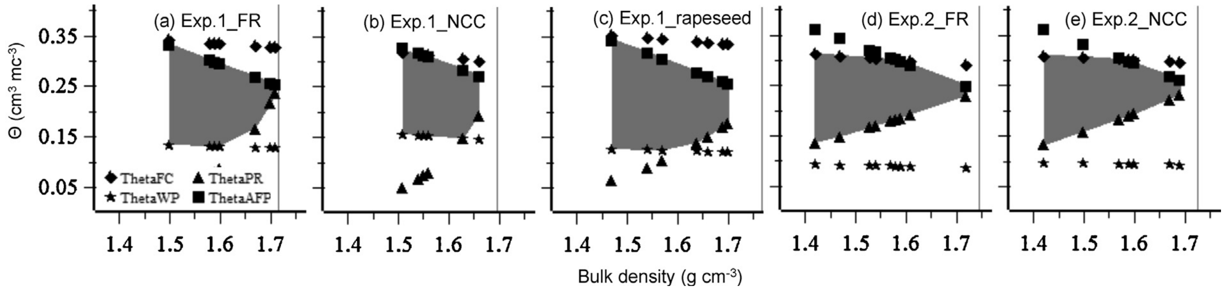

Fig. 1. Graphical representation of the least limiting water range (LLWR) for soil volumetric water content (Θ) versus bulk density (D_b) at critical levels of field capacity (Θ_{FC} at -0.01 MPa), wilting point (Θ_{WP} at -1.5 MPa), 10% air-filled porosity (Θ_{AFP}) and penetration resistance (Θ_{PR}) of 2.5 MPa for soils at the 10–15 cm depth planted in either forage radish (FR), rapeseed (rape), or no cover crop (NCC) in Exp. 1 (a–c) and Exp. 2 (d–e). [†]Vertical gray line in the right side of each figure indicates the critical bulk density (D_{bc}) at which LLWR equaled zero. [‡]Shaded area represents the least limiting water range within mean $D_b \pm$ standard deviation for each cover crop treatment per experiment.

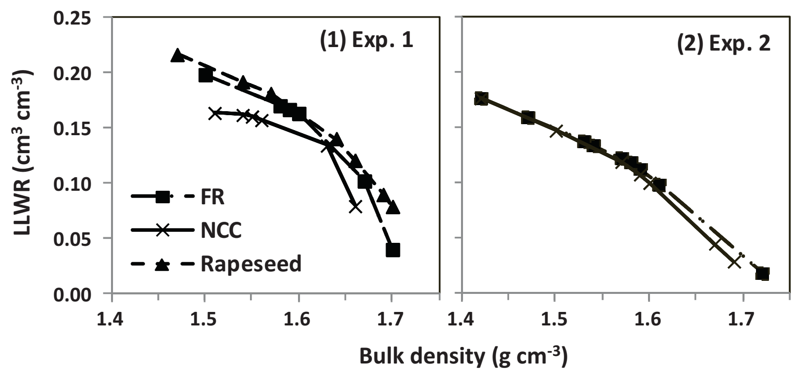

Fig. 2. Least limiting water range (LLWR) versus bulk density (D_b) for soils under forage radish (FR), rapeseed, and no cover crop (NCC) treatments in Exp. 1 and 2.

1 where the term of air-filled porosity was removed. In Exp. 1, air permeability ($\log(k_a)$) was in the order of NC-rapeseed = NC-rye = NC-FR $\geq$ NC-NCC and NC-rapeseed and NC-rye > NC-NCC for the no compaction treatment; in the order of MC-rapeseed = MC-FR = MC-NCC > MC-rye for the medium compaction treatment; and in the order of HC-rapeseed = HC-FR > HC-NCC = HC-rye for the high compaction treatment. The average air permeability for different cover crop treatments across the three compaction levels was in the order of FR = rapeseed > NCC = rye. The average air permeability for three compaction levels across four cover crop treatments was in the order of NC > MC > HC.

Table 7 presents the parameters estimated for the linear equation of $\log(k_a) = \log M + N \times \log(\varepsilon_a)$ for different compaction levels in Exp. 2. Both log M and N values were greater under NC than HC and MC, and N was not significantly different from zero for HC and MC treatments. log M is related to compaction effect and N related to the compaction effect on the slope of $\log(\varepsilon_a)$.

4. Discussion

4.1. Effect of cover crops on least limiting water range

The measurements in Exp. 1 were taken after the experiment had been underway for one and half years with the rotation of fall/winter cover crop – summer crop (maize) – fall/winter cover crop. In Exp. 2, measurements were taken after the experiment had been

Table 5
F-statistical significance for compaction, cover, and air-filled porosity (fa) effects (reduced model) on air permeability at different depth intervals in Exp. 1 and 2.

Source of variance	NDF[a]	Depth interval (cm)							
		0–3		0–6		0–9		0–12	
		F value	Pr > *F*[b]	*F* value	Pr > *F*	*F* value	Pr > *F*	*F* value	Pr > *F*
Exp. 1									
Compaction (com)	2	0.07	0.935	1.89	0.155	1.04	0.357	1.61	0.205
Cover (cov)	3	2.37	0.102	0.20	0.894	1.04	0.377	1.68	0.176
Com × cov	6	0.92	0.457	1.11	0.360	1.04	0.402	2.34	**0.036**
log(fa)	1	0.69	0.411	0.00	0.965	0.03	0.877	0.02	0.880
Com × log(fa)	2	0.13	0.882	1.05	0.354	0.54	0.583	0.94	0.395
Cov × log(fa)	3	2.37	0.102	0.14	0.933	0.69	0.558	1.21	0.310
Exp. 2									
Compaction (com)	2	0.07	0.935	1.53	0.224	1.91	0.157	6.67	**0.002**
Cover (cov)	2	2.37	0.102	0.15	0.862	0.62	0.542	0.87	0.423
Com × cov	4	0.92	0.457	1.60	0.184	1.85	0.131	2.02	0.102
log(fa)	1	0.69	0.411	4.19	**0.045**	5.81	**0.019**	4.97	**0.029**
Com × log(fa)	2	0.13	0.882	1.56	0.218	1.74	0.184	6.32	**0.003**
Cov × log(fa)	2	2.37	0.102	0.08	0.927	0.51	0.604	0.80	0.454

Bold values indicated significant at $a = 0.05$.
[a] NDF is numerator degree of freedom.
[b] Values indicate the probability of a greater *F* value.

Table 6
Soil air permeability ($\log(k_a)$) (μm^2) at 0–12 cm depth in response to compaction (high, medium, and no) and cover crop [forage radish (FR), no cover crop (NCC), rapeseed, and rye] treatments in Exp. 1.

Compaction	Cover crop				
	FR	NCC	Rapeseed	Rye	Avg.
High	1.519cd[†]	1.164e	1.501cd	0.855e	1.261C[b]
Medium	1.538c	1.545c	1.548c	1.223de	1.464B
No	2.157ab	1.929b	2.377a	2.351a	2.203A
Avg.	1.738A[‡]	1.546B	1.809A	1.476B	

[†] Values followed by the same low case letters are not significantly different (Fisher's protected $LSD_{0.05}$).
[‡] Values followed by the same capital letters in the same row or column are not significantly different (Fisher's protected $LSD_{0.05}$).

Table 7
Parameters estimated for soil air permeability ($\log(k_a)$) (μm^2) at 0–12 cm depth in response to compaction and air-filled porosity (ε_a) using $\log(k_a) = \log M + N \times \log(\varepsilon_a)$ in Exp. 2.

Compaction	$\log M$	N
High	3.176b[†]	2.623b
Medium	2.550b	0.944b
No	5.931a	8.082a

[†] Values within the same column followed by the same letters are not significantly different (Fisher's protected $LSD_{0.05}$).

underway for one half year and exposed to a single fall/winter cover crop since the compaction was imposed. There were no significant changes of organic matter content due to different cover crop treatments in the short term. However, we believe that there must be differences in soil structure that was modified by the different cover crops as roots of FR and rapeseed were found to have a greater ability to penetrate compacted soils (Chen and Weil, 2010). As LLWR is defined by the variations of soil water content with bulk density at field capacity (Θ_{FC}), wilting point (Θ_{WP}), 10% air-filled porosity (Θ_{AFP}) and penetration resistance of 2.5 MPa (Θ_{PR}), changes in any of the four parameters would result in changes in LLWR. Because the particle density was the same for all cover crop treatments in each experiment, Θ_{AFP} would vary only with bulk density. While Θ_{FC} may be affected by soil structure, Θ_{WP} represents water content values that are influenced more by texture rather than structure (Letey, 1985). In Exp. 1, the variations of soil water with bulk density at Θ_{FC}, Θ_{WP} and Θ_{AFP} for FR, NCC and rapeseed treatments were very similar (Fig. 1). The only difference among the cover crop treatments was Θ_{PR} which was mostly controlled by soil structure. According to the equation of the soil penetration resistance curve, at a critical penetration resistance of 2.5 MPa, Θ_{PR} increased with Db according to the following power function:

$$\Theta_{PR} = \exp\left(\frac{\ln 2.5 - \ln a}{b}\right) \times {D_b}^{(-c/b)}$$

where a, b and c were fitted parameters in Table 3.

Θ_{PR} is the product of two components: the exponential of $[(\ln 2.5 - \ln a)/b]$ and the bulk density to the power of $(-c/b)$. The first component was 0.00009, 0.00017, and 0.00491 for NCC, FR, and rapeseed in Exp. 2, respectively, and 0.0262 and 0.0334 for FR and NCC in Exp. 2, respectively. The power in the second component was 14.76, 13.88, and 6.76 for FR, NCC, and rapeseed in Exp. 1, respectively, and 2.57 and 2.95 for FR and NCC in Exp. 2, respectively. At the penetration resistance of 2.5 MPa, the increase in bulk density would require a greater increase in soil water content for NCC than for FR in both experiments and for NCC and FR than for rapeseed in Exp. 1. This trend was clearly shown in Fig. 1. The different values of critical bulk density for different cover crops at which LLWR equals zero (or when Θ_{PR} intersects with Θ_{FC}/Θ_{AFP}) reflected the treatment effects on penetration resistance.

It has been reported that LLWR was more sensitive in no-till than in conventional-tillage, because the effect of bio-pores on penetration resistance was greater in no-till (Tormena et al., 1999). This result is supported by research that showed the limiting soil strengths for the root growth of oats (*Avena sativa* L.) were 3.6 MPa and 4.9 MPa in conventional-tillage and no-till systems, respectively, while the presence of bio-pores was not detected by the penetrometer (Ehlers et al., 1983). These results are in agreement with our findings in both experiments that the LLWR and the critical bulk density were greater in FR and rapeseed (Exp. 1 only) treatments than in the NCC treatment under soil compaction. In compacted soils, the limitation of soil penetration resistance in the FR and rapeseed treatments may have been minimized by the presence of root channels.

In Exp. 1, there was also a trend that Θ_{FC} was greater in FR and rapeseed than in the NCC treatment (Fig. 1). Therefore, the LLWR had greater values for the FR and rapeseed treatments (Fig. 2). The increase in soil water content at field capacity for the FR and rapeseed cover crops might be that these cover crop roots created more mesopores and/or improved the aggregation of soil particles. We did not see the same effects of cover crop treatments in Exp. 2. We ascribe the absence of differences mainly to the soil in Exp. 2 having a greater sand content making the effects of bio-pores less pronounced.

4.2. Effect of compaction on least limiting water range

Compaction usually alters the pore size distribution of the bulk soil with a decline of macroporosity and an increase of microporosity, and is reflected by an increase in soil bulk density. The changes in soil structure caused by compaction have three consequences related to LLWR: an increase of soil penetration resistance (Vepraskas, 1984; Tarawally et al., 2004; Servadio et al., 2005), a decline in water content at field capacity (Tarawally et al., 2004) and a reduction of aeration at high water content (Czyź, 2004). For both experiments, compaction decreased the LLWR regardless of the cover crop treatments (Fig. 2), as it usually does for most soils (da Silva and Kay, 1997; Tormena et al., 1999; Zou et al., 2000). Θ_{AFP} was the upper limit for all cover crop treatments when bulk density was greater than 1.50 and 1.55 g cm^{-3} in Exp. 1 and 2, respectively, due to the difference in soil texture between the two fields. In Exp. 2, compaction increased mechanical impedance and thus Θ_{PR} was the lower limit because of the soil's coarse soil texture. Because a heavier machine was used to compact soils and relatively greater clay contents were present in Exp. 1, the change of LLWR reflected the sensitivity of soils to both the axle load of machinery and the influence of soil texture on the response to compaction. The sensitivity of LLWR to management and soil internal properties leads it to be a potential index of soil physical quality (da Silva and Kay, 1997; Tormena et al., 1999; Zou et al., 2000).

4.3. Effects of cover crops on air permeability

As air permeability yields integrated information on the pore geometric effects, any changes of the geometric factors such as total porosity, pore size distribution, pore continuity and shape (Ball, 1981a,b) would result in differences in air permeability. Root channels usually increase total porosity, pore size and continuity. The modification of soil structure by cover crop roots may be reflected in the differences observed for air permeability. In a previous study, we found that rapeseed and FR were able to grow more roots into compacted soils than rye cover crop (Chen and

Weil, 2010). This finding could help explain our results that air permeability for rapeseed and FR treatments (Exp. 1) was greater than that for rye and NCC treatments under high soil compaction (Table 6). The modification of soil structure by different species was also reported by Groenevelt et al. (1984) who observed that air permeability was greater after the growth of forages (alfalfa) than after the growth of corn.

The greater air permeability observed in Exp. 1 for the three cover crop treatments in comparison to the NCC treatment under no compaction may be primarily attributed to the pore continuity being enhanced by the presence of root channels. In Exp. 2, the overall contribution of cover crop roots to air permeability was insignificant because the tractor used for compaction had less axle load than that used for compaction in Exp. 1 and because of the coarser soil texture. Unlike clayey soils, air permeability in sandy and granular soils is highly correlated with macroporosity and would be less affected by pore continuity (Ball et al., 1981).

4.4. Effect of compaction on soil air permeability

Schaffer et al. (2007) reported that trafficking decreased both the porosity and connectivity of macropores. Therefore, it should not be surprising that compaction would decrease soil air permeability. In both experiments, air permeability was reduced by compaction (Tables 6 and 7). These reductions were more evident for different compaction levels in Exp. 1 because the soil's clay content was higher and a heavier axle load tractor was used to establish the compaction treatments. These reductions of air permeability attributed to wheel trafficking are in agreement with Blackwell et al.'s (1990) findings. They reported that air permeability was greatly reduced by a single trafficking pass; and that further passes of trafficking also decreased air permeability, but in a much smaller magnitude. Liang et al. (1995) reported that air permeability was more sensitive than bulk density in reflecting changes of soil compaction and moisture.

According to the mathematical model ($\log k_a = \log M + N \times \log \varepsilon_a$) proposed by Ball et al. (1988), N value (slope) would be greater as pore continuity increases. In Exp. 2, the slope for this linear relationship between $\log(k_a)$ and $\log(\varepsilon_a)$ was the greatest for the no compaction treatment and not significantly different from zero for the medium and high compaction treatments, reflecting the increased tortuosity of the pores as the degree of compaction increased.

5. Conclusion

The degree of compaction caused by tractors and field equipment was affected by the soil texture and the axle load of the tractors and equipment that passed over the field. With greater soil clay content and heavier axle loads, there were greater reductions observed for both LLWR and air permeability. The reduction of LLWR for the compaction treatments was caused by poor aeration at the upper limit and greater mechanical impedance at the lower limit where soil had more clay content. In sandy soils, the reductions of LLWR caused by compaction were often attributed to the increased mechanical impedances at the lower limit. It is postulated that the creation of more root channels in the compacted soils by the rapeseed and FR treatments decreased the lower limits of LLWR by altering the penetration resistance, which produced a broader LLWR and a greater critical bulk density. The two tap-rooted cover crops improved the soil air permeability at the high compaction level in clayey soils in Exp. 1 which was probably due to their greater ability to penetrate the compacted soils. In non-compacted soils or sandy soils, the increases of air permeability by cover crop roots were less pronounced. The increased LLWR and air permeability associated with the FR and rapeseed cover crop treatments under soil compaction suggests that the tap-rooted cover crops may provide a better soil environment for the growth of subsequent cash crops. Further studies on the long-term effects of cover crops on soil physical quality are needed.

Acknowledgments

This study was partially funded by USDA NE-SARE program (grant LNE03-192) and the Harry R. Hughes Center for TAgroT-TEcologyT. We thank Gary Siebel (the University of Maryland) for providing technical support and two anonymous reviewers for constructive feedback.

References

Ball, B.C., 1981a. Modeling of soil pores as tubes using gas permeabilities, gas diffusivities, and water release. J. Soil Sci. 32, 465–481.
Ball, B.C., 1981b. Pore characteristics of soil from two cultivation experiments as shown by gas diffusivities and permeabilities and air filled porosities. J. Soil Sci. 32, 483–498.
Ball, B.C., Bingham, I., Rees, R.M., Watson, C.A., Litterick, A., 2005. The role of crop rotations in determining soil structure and crop growth conditions. Can. J. Soil Sci. 85, 557–577.
Ball, B.C., Campnell, D.J., Douglas, J.T., Henshall, J.K., O' Sullivan, M.F., 1997. Soil structural quality, compaction and land management. Eur. J. Soil Sci. 48, 593–601.
Ball, B.C., Harris, W., Burford, J.R., 1981. A laboratory method measure gas diffusion and flow in soil and other porous materials. J. Soil Sci. 32, 232–233.
Ball, B.C., O'Sullivan, M.C., Hunter, R., 1988. Gas diffusion, fluid flow and derived pore continuity indices in relation to vehicle traffic and tillage. J. Soil Sci. 39, 327–339.
Bengough, A.G., Mullins, C.E., 1990. Mechanical impedance to root-growth – a review of experimental-techniques and root-growth responses. Eur. J. Soil Sci. 41, 341–358.
Beutler, A.N., Centurion, J.F., Silva, A.P., 2005. Soil resistance to penetration and least limiting water range for soybean yield in a haplustox from Brazil. Braz. Arch. Biol. Technol. 48, 863–871.
Blackwell, P.S., Ringrose-Voase, A.J., Jayawardane, N.S., Olsson, K.A., McKenzie, D.C., Mason, W.K., 1990. The use of air-filled porosity and intrinsic permeability to air to characterize structure of macropore space and saturated hydraulic conductivity of clay soils. Eur. J. Soil Sci. 41, 215–228.
Cavalieri, K.M.V., da Silva, A.P., Tormena, C.A., Leão, T.P., Dexter, A.R., Håkansson, I., 2009. Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferrasol in Paraná, Brazil. Soil Tillage Res. 103, 158–164.
Chen, G.H., Weil, R.R., 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331, 31–43.
Chen, G.H., Weil, R.R., 2011. Root growth and yield of maize as affected by soil compaction and cover crops. Soil Tillage Res. 117, 17–27.
Chief, K., Ferre, T., Nijssen, B., 2008. Correlation between air permeability and saturated hydraulic conductivity: unburned and burned soils. Soil Sci. Soc. Am. J. 72, 1501–1509.
Coale, F.J., Costa, J.M., Bollero, G.A., Schlosnagle, S.P., 2001. Small grain winter cover crops for conservation of residual soil nitrogen in the mid-Atlantic Coastal Plain. Am. J. Altern. Agric. 16, 66–72.
Cook, A., Marriott, C.A., Seel, W., Mullins, C.E., 1996. Effects of soil mechanical impedance on root and shoot growth of *Lolium perenne* L, *Agrostis capillaris* and *Trifolium repens* L. J. Exp. Bot. 47, 1075–1084.
Czyź, E.A., 2004. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil Tillage Res. 79, 153–166.
da Silva, A.P., Kay, B.D., 1996. The sensitivity of shoot growth of corn to the least limiting water range of soils. Plant Soil 184, 323–329.
da Silva, A.P., Kay, B.D., 1997. Estimating the least limiting water range of soils from properties and management. Soil Sci. Soc. Am. J. 61, 877.
da Silva, A.P., Kay, B.D., 2004. Linking process capability analysis and least limiting water range for assessing soil physical quality. Soil Tillage Res. 79, 167–174.
da Silva, A.P., Kay, B.D., Perfect, E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58, 1775–1781.
Dane, J.H., Hopmans, J.W., 2002. Water retention and storage. In: Campbell, G.S., Horton, R., Jury, W.A., Nielsen, D.R., van Es, H.M., Wierenga, P.J., Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 4: Physical Methods. Soil Science Society of America, Inc., Madison, WN, pp. 671–757.
Dean, J.E., Weil, R.R., 2009. Brassica cover crops for nitrogen retention in the mid-Atlantic coastal plain. J. Environ. Qual. 38, 520–528.
Dörner, J., Horn, R., 2009. Direction-dependent behaviour of hydraulic and mechanical properties in structured soils under conventional and conservation tillage. Soil Tillage Res. 102, 225–232.
Drury, C.F., Zhang, T.Q., Kay, B.D., 2003. The non-limiting and least limiting water ranges for soil nitrogen mineralization. Soil Sci. Soc. Am. J. 67, 1388–1404.
Ehlers, W., Kopke, U., Hesse, F., Bohm, W., 1983. Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil Tillage Res. 3, 261–275.

Groenevelt, P.H., Kay, B.D., Grant, C.D., 1984. Physical assessment of a soil with respect to rooting potential. Geoderma 34, 101–114.
Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems – a review of the nature, causes and possible solutions. Soil Tillage Res. 82, 121–145.
Hettiaratchi, D.R.P., 1990. Soil compaction and plant-root growth. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 329, 343–355.
Ishaq, M., Hassan, A., Saeed, M., Ibrahim, M., Lal, R., 2001. Subsoil compaction effects on crops in Punjab, Pakistan I. Soil physical properties and crop yield. Soil Tillage Res. 59, 57–65.
Jalbert, M., Dane, J.H., 2003. A handheld device for intrusive and nonintrusive field measurements of air permeability. Vadose Zone J. 2, 611–617.
Lapen, D.R., Topp, G.C., Gregorich, E.G., Curnoe, W.E., 2004. Least limiting water range indicators of soil quality and corn production, eastern Ontario, Canada. Soil Tillage Res. 78, 151–170.
Leao, T.P., da Silva, A.P., Macedo, M.C.M., Imhoff, S., Euclides, V.P.B., 2006. Least limiting water range: a potential indicator of changes in near-surface soil physical quality after the conversion of Brazilian Savanna into pasture. Soil Tillage Res. 88, 279–285.
Leao, T.P., da Silva, A.P., Perfect, E., Tormena, C.A., 2005. An algorithm for calculating the least limiting water range of soils. Agron. J. 97, 1210–1215.
Letey, J., 1985. Relationship between soil physical properties and crop production. Adv. Soil Sci. 1, 277–294.
Liang, P., Bowers Jr., C.G., Bowen, H.D., 1995. Finite element model to determine the shape factor for soil air permeability measurements. Trans. ASAE 38, 997–1003.
Loll, P., Moldrup, P., Schjønning, P., Riley, H., 1999. Predicting saturated hydraulic conductivity from air permeability: application in stochastic water infiltration modeling. Water Resour. Res. 35, 2387–2400.
Mualem, Y., 1976. New model for predicting hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12, 513–522.
Saqib, M., Akhtar, J., Qureshi, R.H., 2004. Pot study on wheat growth in saline and waterlogged compacted soil I. Grain yield and yield components. Soil Tillage Res. 77, 169–177.
Schaffer, B., Stauber, M., Muller, R., Schulin, R., 2007. Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. Eur. J. Soil Sci. 58, 1062–1073.
Servadio, P., Marsili, A., Pagliali, M., Pellegrini, S., Vignozzi, N., 2001. Effects on some clay soil qualities following the passage of rubber-tracked and wheeled tractors in central Italy. Soil Tillage Res. 61, 143–155.
Servadio, P., Marsili, A., Vignozzi, N., Pellegrini, S., Pagliai, M., 2005. Effects on some soil qualities in central Italy following the passage of four wheel drive tractor fitted with single and dual tires. Soil Tillage Res. 84, 87–100.
Soil Science Society of America, 1996. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI.
Stirzaker, R.J., Passioura, J.B., Wilms, Y., 1996. Soil structure and plant growth: Impact of bulk density and biopores. Plant Soil 185, 151–162.
Tarawally, M.A., Medina, H., Frometa, M.E., Itza, C.A., 2004. Field compaction at different soil-water status: effects on pore size distribution and soil water characteristics of a Rhodic Ferralsol in Western Cuba. Soil Tillage Res. 76, 95–103.
Topp, G.C., Zebchuk, W., 1979. The determination of soil-water desorption curves for soil cores. Can. J. Soil Sci. 59, 19–26.
Tormena, C.A., da Silva, A.P., Libardi, P.L., 1999. Soil physical quality of a Brazilian Oxisol under two tillage systems using the least limiting water range approach. Soil Tillage Res. 52, 223–232.
Tuli, A., Hopmans, J.W., Rolston, D.E., Moldrup, P., 2005. Comparison of air and water permeability between disturbed and undisturbed soils. Soil Sci. Soc. Am. J. 69, 1361–1371.
Unger, P.W., Kaspar, T.C., 1994. Soil compaction and root-growth – a review. Agron. J. 86, 759–766.
van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.
Vepraskas, M.J., 1984. Core index of loamy sands as influenced by pore size distribution and effective stress. Soil Sci. Soc. Am. J. 48, 1220–1225.
Vrindts, E., Mouazen, A.M., Maertens, K., Maleki, M.R., Ramon, H., Baerdemaeker, J.D., 2005. Management zones based on correlation between soi compaction, yield and crop data. Biosyst. Eng. 92, 419–428.
Williams, S.M., Weil, R.R., 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68, 1403–1409.
Wu, L., Feng, G., Letey, J., Ferguson, L., Mitchell, J., McCullough-Sanden, B., Markegard, G., 2003. Soil management effects on the nonlimiting water range. Geoderma 114, 401–414.
Zou, C., Sands, R., Buchan, G., Hudson, I., 2000. Least limiting water range: a potential indicator of physical quality of forest soils. Aust. J. Soil Res. 38, 947–958.